THE NUTRITIONAL VALUE OF HYBRID RYE FED TO GROWING PIGS

BY

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THESIS

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ABSTRACT

Three experiments were conducted to determine the nutritional composition and digestibility of hybrid rye and other cereal grains fed to growing pigs. In Exp. 1, the objective was to determine the standardized ileal digestibility (SID) of AA in 3 varieties of hybrid rye and in one source of barley, wheat, and corn. Seven ileal cannulated barrows (initial BW = 26.1 ± 2.4 kg) were randomly allotted to a 7 × 7 Latin square design with 7 periods and 7 experimental diets. Six diets included one cereal grain as the sole source of AA, and a N-free diet was used to determine basal endogenous losses of CP and AA. Wheat and barley contained more CP and indispensable AA than hybrid rye, but hybrid rye contained more indispensable AA compared with corn. The SID of CP and most indispensable AA was greater ($P < 0.05$) in barley, wheat, and corn than in the 3 varieties of rye but concentrations (g/kg) of SID AA in hybrid rye were close to values in corn. In Exp. 2, the objective was to determine the standardized total tract digestibility (STTD) of P in 3 varieties of hybrid rye and in one source of barley, wheat, corn, and sorghum. One hundred twelve growing barrows (initial BW = 13.7 ± 1.3 kg) were allotted to a randomized complete block design with 4 blocks of 28 pigs, 14 experimental diets, and 8 total replicate pigs per treatment. Each diet contained one of the cereal grains as the sole source of P, and there were 2 diets formulated with each cereal grain; the first contained no microbial phytase, and the second contained 1,000 units of microbial phytase per kg of diet. Among the diets that did not include microbial phytase, one hybrid of rye had greater ($P < 0.05$) STTD of P than wheat, corn, and sorghum. Among the diets containing microbial phytase, there was no difference in STTD of P among hybrid rye, barley, and corn. Microbial phytase improved ($P < 0.05$) the STTD of P in all cereal grains. In Exp. 3, the objectives were to determine the apparent ileal digestibility (AID) and the apparent total tract digestibility (ATTD) of energy, starch, and total dietary fiber (TDF), as well as the ME in 2 varieties of hybrid rye and in one source of barley, wheat, corn, and sorghum. Twenty-four ileal cannulated barrows (initial BW = 28.1 ± 3.0 kg) were randomly allotted to a 2-period experimental design with 6 experimental diets and 8 total replicate pigs per diet. Each diet consisted of 97% of one cereal grain, thus, the cereal grain was the sole contributor of energy and carbohydrates to the diet. The concentration of TDF was greatest in barley (19.0%), whereas hybrid rye contained 15.2% to 18.1% TDF, and wheat, corn, and sorghum contained less. In all grains, the AID of starch was greater than 90%, and the ATTD of starch was nearly 100%. The AID of TDF was less than 35% for all cereal grains, but the ATTD of TDF was greater ($P < 0.05$) in the 2 hybrid ryes than in the other ingredients. The AID of GE was greater ($P < 0.05$) in wheat, corn, and sorghum than in barley and hybrid rye. The ATTD of GE was also greater ($P < 0.05$) in corn than in hybrid rye, barley, and sorghum, but there were no differences between corn and wheat, nor among one hybrid of rye, wheat, and sorghum. On a DM basis, the ME in the 2 sources of hybrid rye was 3,459 and 3,499 kcal/kg, respectively, which was less ($P < 0.05$) than in corn and wheat. In conclusion, the SID of AA in hybrid rye is less than in other cereal grains; however, because of the greater concentration of AA in hybrid rye than in corn, the quantities of standardized ileal digestible AA are not different between corn and hybrid rye. Without microbial phytase, the STTD of P in hybrid rye is greater than in other cereal grains, which is likely due to the greater intrinsic phytase activity in rye, and the addition of microbial phytase improves the STTD of P in all cereal grains. Hybrid rye results in reduced pre-cecal absorption of energy compared with wheat, corn, and sorghum, but because hindgut fermentation of fiber is greater in rye than in other cereal grains, the ME in hybrid rye is not different from the ME in barley and sorghum, but less than in corn and wheat.

Keywords: amino acids, dietary fiber, energy, growing pigs, hybrid rye, phosphorus digestibility

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CHAPTER 1: INTRODUCTION

Rye is not typically included in diets for swine in large amounts because it is associated with anti-nutritional factors, ergot poisoning, and poor growth performance (Friend and MacIntyre, 1969; Antoniou et al., 1981; Bederska-Łojewska et al., 2017). However, the advent of hybrid rye has mitigated some of the previous concerns for feeding rye to pigs. New hybrids of rye have reduced concentrations of anti-nutritional factors, like trypsin inhibitors and alkylresorcinols, as well as reduced susceptibility to ergot contamination (Makarska et al., 2007, cited by Schwarz et al., 2015; Miedaner and Geiger, 2015). The new hybrids also offer several agronomic benefits, including high yield compared with older cultivars of rye and other small grains, drought tolerance, pest resistance, and winter hardiness (Wolski, 1974, cited in Boros et al., 1993; Evans and Scoles, 1976; Geiger and Miedaner, 2009; Jürgens et al., 2012). Due to the improvements attained through plant breeding, hybrid rye may become an attractive option for farmers to grow in areas with long, cold winters or soil not suitable for growing corn.

Other than a livestock feed, rye is used for flour in the baking industry, as an ingredient for whiskey distillers, and as a substrate for biogas production (Bengtsson et al., 1992; Geiger and Miedaner, 2009; Balcerek et al., 2016). Rye is similar to other small grains, such as wheat and barley, as it has a high concentration of starch and greater concentrations of protein and fiber than corn (Cervantes-Pahm et al., 2013; 2014; Rodehutscord et al., 2016). Furthermore, the fiber fraction in rye is more fermentable than in other cereal grains and may provide gut health benefits to pigs (Karppinen et al., 2003; Le Gall et al., 2010; Bach Knudsen et al., 2005; 2016; 2017)

Although hybrid rye is likely a suitable feed ingredient for pigs, there is limited information about the digestibility of energy and nutrients in hybrid rye, and it is unclear if hybrid rye is nutritionally different from older cultivars of rye that are included in current feed tables (Jürgens et al., 2012; Strang et al., 2016). Furthermore, much of the swine nutrition research conducted with hybrid rye in Europe has compared rye with other small grains, such as barley, but no research has been conducted comparing hybrid rye with corn, the most common grain fed to pigs in the U.S. (Schwarz et al., 2015; 2016; Sørensen and Nymand, 2018). Therefore, the objectives of this research were to:

1. Determine the apparent and standardized ileal digestibility of CP and AA in hybrid rye, barley, wheat, and corn fed to growing pigs;

2. Determine the apparent and standardized total tract digestibility of P in hybrid rye, barley, wheat, corn, and sorghum fed to growing pigs; and

3. Determine the apparent ileal and total tract digestibility of energy and carbohydrates, as well as the DE, ME, and NE in hybrid rye, barley, wheat, corn, and sorghum fed to growing pigs.

It was hypothesized that hybrid rye will provide digestible quantities of AA, P, and energy that are comparable to other cereal grains, including barley, wheat, corn, and sorghum.

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CHAPTER 2: RYE: LITERATURE REVIEW

INTRODUCTION

Rye (*Secale cereal* L.) is a cereal grain predominantly grown in Europe. In 2016, 12.9 million tons of rye were produced in the world, and Germany, Russia, Poland, Belarus, and Denmark were the top rye-producing countries, accounting for approximately 70% of global production (FAOSTAT, 2016). Rye production has declined in recent decades, and less rye is produced than of all other major cereal grains, including corn, wheat, barley, sorghum, millet, oats, and triticale (FAOSTAT, 2016). Like wheat, one of the primary uses for rye is bread making, but it can also be used for distilling alcohol, producing biogas, and as a feed for livestock (Bengtsson et al., 1992; Geiger and Miedaner, 2009; Balcerek et al., 2016). Rye is not presently used in large quantities for livestock feed in North America; however, with the advent of rye hybrids, which have superior agronomic characteristics (Jürgens et al., 2012), utilization may increase.

AGRONOMIC CHARACTERISTICS OF HYBRID RYE

Winter rye is planted in late summer to early fall, enters a dormancy period over winter, and continues growth in early spring (Blecharczyk et al., 2016). If used as a cover crop, rye is killed in the spring before it is fully mature (Krueger et al., 2011). If planted with the intention to harvest, it is left to grow until late spring to early summer, depending on the moisture content and desired end usage (Hübner et al., 2011; Blecharczyk et al., 2016). In 2018, less than 20% of the approximately 2 million acres of rye planted in the U.S were harvested (USDA, 2018). Population rye is often used as a cover crop because it improves soil integrity and protects against nutrient loss and soil erosion (Kaspar et al., 2001; 2007), but planting rye for the purpose of harvesting will also afford these benefits to the environment. Rye that is combined may ultimately be used in the human food and distilling industries or for swine and poultry feed, and the straw residue may be used for animal bedding. The crop may also be chopped as whole-plant silage for ruminant feed or biogas (Geiger and Miedaner, 2009; Joo et al., 2017).

Rye can grow on poor, sandy, and acidic soils, it is very resilient to cold stress, and it is more drought tolerant than other grains due to its deep roots (Wolski, 1974, cited in Boros et al., 1993; Evans and Scoles, 1976; Geiger and Miedaner, 2009; Jürgens et al., 2012). In controlled dry and wet growing conditions, rye faired better than wheat and barley, producing the greatest above-ground DM yield and coolest canopy, suggesting rye is a suitable crop for variable environmental conditions (Schittenhelm et al., 2013). Rye is resistant to many typical pests, diseases, and fungi that affect other cereals, although the extent is largely dependent on the environment (Geiger and Miedaner, 2009). Cover crops are known to provide early-season weed control (Teasdale, 1996); therefore, it is possible that adding rye to a crop rotation can disrupt weed cycles and improve whole-farm production as well (Sullivan et al., 2005).

The first hybrid of rye was released in 1984, and as of 2014, approximately 80% of the rye grown in Germany is hybrid rye (Laidig et al., 2017). The most important feature of hybrid rye over population rye is its increased yield potential, which can also surpass yields of other cereal grains when managed correctly (Geiger and Miedaner, 2009). The University of Minnesota and North Dakota State University have conducted multiple-year field trials of high-producing rye varieties, including 2 hybrids developed by KWS (Bergen, Germany). Over 5 Minnesota locations in the years 2016 through 2018, one of the hybrids yielded 10.2 to 12.8 t/ha, and the second hybrid yielded 9.5 to 10.7 t/ha (Wiersma et al., 2018). In comparison, the next highest-yielding population variety ranged from 6.6 to 8.5 t/ha, whereas another variety ranged from 2.5 to 4.4 t/ha. On less fertile ground in Hettinger, ND, the 2-year average for one of the hybrids of rye was 5.3 t/ha, whereas the population varieties yielded only 2.6 to 4.2 t/ha (North Carolina State University, 2018).

The basis of hybrid rye breeding is to maximize heterosis by breeding 2 genetically different inbred rye lines to produce a superior F1 hybrid, as described by Geiger and Miedaner (2009). The purpose of using inbred lines is to reduce genetic variation and ensure a uniform F1 progeny. Producing hybrid rye seed is challenging because rye is naturally a cross-pollinator, meaning it cannot self-fertilize. Therefore, self-fertility must first be established using backcrossing in order to develop multiple highly inbred lines. Two inbred lines, one cytoplasmic male sterile (**CMS**) line that does not produce pollen and one maintainer line that produces pollen, are crossed to produce the mother line seed parent. The maintainer line is planted in stripes among the CMS lines and is removed after flowering to ensure all seeds originate from the CMS line. Once the seed parent is established, it is crossed with the restorer, which is a synthetic inbred line that produces pollen. Successful restorer genes, specifically *Rfp1* and *Rfp2*, are native to Iranian and Argentinian rye. Because the seed parent and restorer are genetically different, but uniform within lines, the hybrid offspring of the cross is a genetically uniform, high producing seed.

New hybrids of rye also have reduced anti-nutritional factors (Makarska et al., 2007, cited by Schwarz et al., 2015), and their predisposition for ergot infection has been partially mitigated (Miedaner and Geiger, 2015). Because rye is a cross-pollinating crop, it is more susceptible to ergot than other grains, especially when pollen shedding is non-synchronous with flowering. Hybrid crops developed from CMS lines are particularly susceptible due to low pollen shedding, but the level of contamination of ergot in rye can be controlled through breeding techniques and management of the grain, as described by Miedaner and Geiger (2015). Commercially sold hybrid rye seed contains a novel trait, known as Pollen Plus, which utilizes the pollen restorer genes *Rfp1* and *Rfp2* to improve the efficiency of pollen shedding and minimize the opportunity for ergot to infect the unfertilized seed heads. Other breeding goals for hybrid rye, such as reducing the time flowers are open for pollination and improving flowering synchronicity, also minimize the risk of ergot infection. Crop management techniques to reduce ergot include maximizing the cereal stand by planting at the optimal seed rate and fertilizing with adequate N, as well as harvesting the perimeter of the field separately from the rest of the field. Furthermore, ergot contaminated rye grain can be mechanically cleaned after harvest by means of gravimetric or color separation of the grain and sclerotia. Mechanical cleaning is standard procedure at mills that handle large quantities of rye grain, and it can eliminate the risk of feeding toxic alkaloids to humans and animals.

NUTRIENT COMPOSITION OF RYE

Most of the energy in rye is derived from starch, which comprises 50 to 65% of the grain (Nilsson et al., 2000; Jondreville et al., 2001; Schwarz et al., 2015; Strang et al., 2016). The GE in rye is approximately 4,400 kcal/kg on a DM basis (Cervantes-Pahm et al., 2013; Rodehutscord et al., 2016). Rye contains between 12 and 17% dietary fiber, which is greater than observed in wheat, sorghum, and corn, but less than in barley (Bach Knudsen, 1997; Hansen et al., 2003; Salmenkallio-Marttila and Hovinen, 2005; NRC, 2012; Cervantes-Pahm et al., 2013; Strang et al., 2016). Dietary fiber includes oligosaccharides, non-starch polysaccharides (**NSP**), resistant starch, and lignin (NRC, 2012).

Rye has greater concentrations of fructans than other cereal grains (Hansen et al., 2003; Karppinen, 2003). In older literature, short chains of fructose units are referred to as fructooligosaccharides, whereas fructopolysaccharides are longer, more complex chains of fructose units (Hansen et al., 2003). Both fructooligosaccharides and fructopolysaccharides are sometimes categorized under the general term, "fructans." However, according to Englyst et al. (2007), any carbohydrate that resists pancreatic and small intestinal digestion and is soluble in 80% ethanol may be referred to as a non-digestible or resistant oligosaccharide. Therefore, by this definition, there is no limit to the number of monomers present in an oligosaccharide, and all soluble indigestible fructose polymers can be referred to as fructooligosaccharides. However, some researchers still make the distinction between fructans and fructooligosaccharides, categorizing fructooligosaccharides as partially hydrolyzed fructans (Li and Kim, 2013). Nevertheless, there are 2 broad classes of fructooligosaccharides: levan and inulin (Vijn and Smeekens, 1999). Levan synthesis primarily relies on microbial production, but inulin is intrinsic to a variety of plants, including rye (Yamamoto et al., 1999; Karppinen et al., 2003). Whereas the fructose units in levans are mainly linked by β-2,6 bonds, inulin monomers are mainly linked by β-2,1 bonds (Dedonder, 1966).

Published values for the concentration of fructans in rye vary depending on the chemical analysis performed. When analyzed via the procedure described by Bach Knudsen (1997), the concentration of fructans in rye is approximately 3% (Bach Knudsen, 1997; Lærke et al., 2015; Strang et al., 2016; Rodehutscord et al., 2016). However, when analyzed enzymatically by the method described by McCleary et al. (2000), values for fructans range from 4.5 to 6.6% on a DM basis (Hansen et al., 2003; Karppinen et al., 2003). Fructans are not digested in the small intestine but are degraded rapidly in the large intestine and are considered a prebiotic that may improve animal and human gut health (Karppinen et al., 2003). Consuming 8 g fructans per day increased the presence of *Bifidobacterium* and *Lactobacillus* and reduced the presence of *Escherichia coli* and *Clostridium* in human gut microbial populations (Bouhnik et al., 2007). Fecal *Lactobacillus* concentrations were greater and *Escherichia coli* concentrations were reduced when fructans were supplemented to finishing pigs at 0.1 or 0.2% of the diet (Zhao et al., 2013). Fructan supplementation also resulted in increased ADG, G:F, and apparent total tract digestibility (**ATTD**) of DM and GE (Zhao et al., 2013). Consumption of fructans may also reduce gas emissions, as the concentration of fecal skatole, the compound partially responsible for boar taint and manure odor, was reduced when 5% inulin extract was supplemented to pigs (Rideout et al., 2004). The concentration of fructans in rye may elicit similar benefits when fed to pigs.

Non-starch polysaccharides are present in high proportions in rye, with arabinoxylans, mixed-linked β-glucans, and cellulose being most abundant (Bach Knudsen, 1997). On a DM basis, the concentration of arabinoxylans in rye is reported to be between 6 and 12% but is more frequently reported to be 8 to 9% (Hansen et al. 2003; Salmenkallio-Marttila and Hovinen, 2005; Jürgens et al., 2012; Strang et al., 2016; Rodehutscord et al., 2016). Rye contains more soluble arabinoxylans than other grains, which is correlated with increased digesta viscosity (Jürgens et al., 2012; Kasprzak et al., 2012). The concentration, structure, degree of substitution, and solubility of arabinoxylans are influenced by plant genotype and growing conditions (Drews and Seibel, 1976; Bengtsson et al., 1992; Hansen et al., 2003; Jürgens et al., 2012; Rodehutscord et al., 2016). These characteristics of arabinoxylans can impact nutrient digestibility when rye is fed to monogastric animals (Fengler and Marquardt, 1988; Petterson and Åman, 1989; Nilsson et al., 2000; Ragaee et al., 2001; Bach Knudsen et al., 2005; Le Gall et al., 2009; Jürgens et al., 2012;

Zuber et al., 2016). Arabinoxylans are present in both the endosperm and the outer tissues of rye grain, and the structure and solubility of arabinoxylans differ depending on the location origin of the fiber (Glitsø et al., 1998; 1999). Arabinoxylans may also form bonds with other fiber components, and there is a high degree of structural variation among sources, which is further evidence of the complexity of rye fiber (Vinkx and Delcour, 1996).

Rye contains 1.5 to 2.5% mixed-linked β-glucans and approximately 1.5% cellulose on a DM basis (Bach Knudsen, 1997; Salmenkallio-Marttila and Hovinen, 2005; Strang et al., 2016). Mixed-linked β-glucans are present in greater concentrations in barley and oats than in rye, and they are highly fermentable (Bach Knudsen and Hansen, 1991; Bach Knudsen, 1997; Rodehutscord et al., 2016). Although the β-1,3 and β-1,4 bonds present in mixed-linked β-glucans are not digestible by endogenous enzymes in the pig, β-glucans provide energy to the pig as a result of microbial fermentation (Bach Knudsen and Hansen, 1991, O'Shea et al., 2010). Cellulose, on the other hand, is indigestible and less fermentable in monogastric animals than other fiber fractions (Bach Knudsen et al., 2005).

Resistant starch is considered a component of dietary fiber and is defined as starch that escapes small intestinal digestion (Englyst et al., 1992; FDA, 2018). The concentration of resistant starch in rye is difficult to determine. By enzymatic isolation, resistant starch has been reported as <1% in rye, but published values for the apparent ileal digestibility (**AID**) of rye starch in pigs indicate that the concentration of resistant starch in rye may be greater than 1% (Cervantes-Pahm et al., 2013; Laerke et al., 2015; Buksa, 2018). The final main component of dietary fiber is lignin. The concentration of Klason lignin in rye is 1 to 2%, whereas the concentration of ADL is 0.7 to 0.9% (Lærke et al., 2015; Strang et al., 2016; Rodehutscord et al., 2016). In feed ingredients, the presence of lignin in large amounts is undesirable because lignin is not degradable by endogenous enzymes nor fermentable by microbes, and it reduces the digestibility of other nutrients (Wenk, 2001).

The concentration and composition of fiber varies among rye sources, and the same is true for the concentration of CP. The amount of N present in the grain depends on genotype, growing conditions, and fertilization rate (Fowler et al., 1990; Jürgens et al., 2012). In addition, newer cultivars of hybrid rye have reduced CP compared with older cultivars of population rye (NRC, 2012; Strang et al., 2016; Laidig et al., 2017). Published values for the concentration of CP in hybrid rye range from 8 to 13% (Jürgens et al., 2012; Pieszka et al., 2015; Schwarz et al., 2015; Strang et al., 2016) with an average of 10%, whereas NRC (2012) reports 11.7% CP in rye. Rye contains more Lys than wheat, barley, and corn, with an average concentration of 0.4% (Cervantes-Pahm et al., 2014; Rodehutscord et al., 2016; Strang et al., 2016). The concentration of Met, Thr, and Trp in rye is approximately 0.2%, 0.3%, and 0.1%, respectively (Cervantes-Pahm et al., 2014; Strang et al., 2016).

Like other cereal grains, the concentration of Ca in rye is minimal – typically less than 0.05%, although occasionally up to 0.08% (NRC, 2012; Rodehutscord et al., 2016). Phosphorus, however, is more abundant in rye. The concentration of total P is 0.3 to 0.4% in rye, but the majority is bound to phytate (Lott et al., 2000; Rodehutscord et al., 2016). A unique characteristic of rye, however, is its high intrinsic phytase activity, which can liberate P from phytate and improve P digestibility (Pointillart et al., 1987). Rye can contain up to 4,000 units of intrinsic phytase per kg of grain, whereas wheat contains only half as much intrinsic phytase activity, and corn and sorghum are practically devoid of phytase (Rodehutscord et al., 2016).

DIGESTIBILITY OF NUTRIENTS AND ENERGY

The digestibility of most nutrients in older cultivars of rye is greater than in new cultivars of hybrid rye, although few studies have evaluated the digestibility of hybrid rye in pigs thus far (Strang et al., 2016). Friend and MacIntyre (1969) reported that the digestibility of CP was greater in rye (85 to 89%) than in barley. The standardized ileal digestibility (**SID**) of CP is 83% and 79% in rye and barley, respectively (NRC, 2012). However, the SID of N in rye has been reported to be as low as 68%; therefore, it is possible that NRC table values overestimate the digestibility of CP in newer cultivars of rye (Brestenský et al., 2013). Lærke et al. (2015) determined the AID of N to be approximately 45% in coarsely ground rye, and 51% in finely ground rye – significantly less than in coarse and fine wheat. Results of most published research indicates that the digestibility of CP in rye is similar to barley, but less than in other cereal grains.

In hybrid rye specifically, the SID of CP was determined to be 73% in pigs, however, the experimental design did not allow for determination of SID of CP or AA in any comparative ingredients to validate the results for hybrid rye (Strang et al., 2016). Like other cereal grains, the first 2 limiting AA in rye are Lys and Met (Brestenský et al., 2013). The SID of Lys, Met, Thr, and Trp was 62%, 75%, 64%, and 65%, respectively, which are less than reported values for rye (NRC, 2012). Conversely, in corn, the most predominantly fed cereal grain to pigs in the U.S., the SID of Lys, Met, Thr, and Trp is 74%, 83%, 77%, and 80%, respectively (NRC, 2012). It is hypothesized that the reason for the lower AA digestibility in rye than in corn is that rye contains more indigestible protein entrapped in the insoluble fiber portion of the grain, and also because greater proportions of fiber in rye increase endogenous losses of AA (Jondreville et al., 2001).

The standardized total tract digestibility (**STTD**) of P is 50% in rye (NRC, 2012); however, this value is based on only 1 observation. The ATTD of P in rye was reported to be 60% if microbial phytase was included in the diet (Nørgaard et al., 2016). Based on results of recent research, the digestibility of P is likely greater in rye than in corn, barley, and sorghum, but less than in wheat (NRC, 2012). The high intrinsic phytase activity of rye may be responsible for the greater digestibility of P in rye if microbial phytase is not included in the diet (Rodehutscord et al., 2016).

The concentration of ME in rye fed to pigs is approximately 3,770 kcal per kg on a DM basis, which is less than in corn, dehulled barley, sorghum, and wheat (Cervantes-Pahm et al., 2013). It is not clear if the ME in hybrid rye is different from the ME in older cultivars of rye. The AID of GE in rye is approximately 62%, which is also less than in other cereal grains (Nitrayová et al., 2009; Cervantes-Pahm et al., 2013). Most energy obtained from rye is derived from starch, which is 92 to 97% digestible (Cervantes-Pahm et al., 2013; Laerke et al., 2015). The ATTD of GE in rye is reported to be between 85 and 90% which is less than or equal to other grains (Nitrayová et al., 2009; Cervantes-Pahm et al., 2013). The hindgut disappearance of GE, however, is greater in rye than in other cereal grains, due to the fiber being more fermentable in rye (Le Gall et al., 2010; Cervantes-Pahm et al., 2013). Microbial xylanase supplementation to rye diets resulted in a numerical increase of 3.3% in the AID of GE and a significant increase of 1.7% in the ATTD of GE (Nitrayová et al., 2009); however, results of other studies indicate negligible effects of xylanase supplementation on digestibility of energy in rye (Nørgaard et al., 2016; Schwarz et al., 2016).

The difference in AID and ATTD of GE is due to the extent of microbial fermentation in the hindgut. Microbial fermentation of fiber results in synthesis of short-chain fatty acids that can be absorbed by the pig for energy utilization (NRC, 2012). Degradation of NSP is generally low in the foregut, typically around 10 to 15% in rye, but as is true in the hindgut, degradation occurs due to microbial fermentation rather than by endogenous enzymes (Jensen and Jørgensen, 1994; Nitrayová et al., 2009; Lærke et al., 2015). Microbial fermentation is more pronounced in the hindgut, and the ATTD of NSP can be up to 76% in rye (Nørgaard et al., 2016). Supplementing diets with microbial xylanase may reduce digesta viscosity and improve digestibility of NSP, however, the effects are greater in wheat-based diets than in rye-based diets (Nitrayová et al., 2009; Lærke et al., 2015).

Soluble fiber is more readily fermented than insoluble fiber, and the extent of solubility of arabinoxylan is influenced by the degree of substitution on the xylose backbone and the presence of cross-linkages with other molecules (Bach Knudsen and Hansen, 1991; Karppinen, 2003; Le Gall et al., 2009). Rye arabinoxylan is more easily fermented than wheat arabinoxylan because it is more soluble (Le Gall et al., 2010). Arabinoxylan fermentability also depends on the location of the fiber in the grain. Arabinoxylan derived from the inner endosperm is highly soluble and degradable; however, arabinoxylan from the outer pericarp is entirely undegraded in the pig (Glitsø et al., 1999). Arabinoxylan derived from the aleurone layer, which is located between the inner endosperm and outer pericarp, is moderately fermentable, but the process is slow (Glitsø et al., 1999). Although rye arabinoxylan is more fermentable than arabinoxylans in other cereal grains, the high concentration of dietary fiber in rye may reduce the digestibility of other nutrients (Le Gall et al., 2009).

LIMITATIONS OF FEEDING RYE

Historically, rye was not included in diets for animals in large quantities because it was associated with poor performance attributed to ergot contamination, poor palatability, and presence of anti-nutritional factors (Friend and MacIntyre, 1969; Antoniou et al., 1981; Bederska-Łojewska et al., 2017). However, recent developments in hybrid breeding have mitigated some of the risks previously associated with feeding rye to pigs.

Ergot alkaloids are toxic compounds caused by contamination of small grains by *Claviceps* fungi, and they can cause detrimental health effects when consumed by animals at concentrations as low as 100 µg per kg grain (Coufal-Majewski et al., 2016). Besides posing a health risk, ergot also slightly reduces yield because dark-colored masses of fungal material, referred to as ergot sclerotia, accumulate where a seed would otherwise grow. Nevertheless, the greatest economic impact on infected grain value is due to reduction in quality rather than yield (Harper and Seaman, 1980). The sclerotia bodies contain ergot alkaloids and are also involved in the production of spores for the propagation of the ergot lifecycle (Nicholson, 2007). In the E.U., rye is considered unfit for human consumption if it contains more than 0.05% ergot sclerotia by weight and unfit for animal consumption if it exceeds 0.1% by weight. Likewise, in the U.S., rye is considered "ergoty" if more than 0.3% of the grain contains ergot sclerotia, at which point the grain's value is reduced (Miedaner and Geiger, 2015). However, the advent of the Pollen Plus trait in hybrid rye reduces the plant's vulnerability to ergot infection.

Like other cereals, rye may contain mycotoxins other than those caused by ergot. In one study, rye and oats contained more ergosterol, deoxynivalenol (**DON**), fusarenone X, 3-acetyl DON, 15-acetyl DON, nivalenol, and total mycotoxins than wheat, barley, and triticale (Stuper-Szablewska and Perkowski, 2017). The concentration of mycotoxins is variable and influenced by environmental growing conditions and crop management; therefore, monitoring the presence of mycotoxins in animal feed is crucial (Grajewski et al., 2012).

Another perceived limitation to feeding rye to livestock is its poor palatability, as rye is more bitter than other small grains, such as wheat (Katina et al., 2014). High concentrations of insoluble arabinoxylans in flour, despite improving dough quality, have a negative impact on the taste of rye bread (Meuser and Suchow, 1986, cited by Hansen et al., 2003). Negative feeding behavior, including feed spillage and beak problems, in broilers fed rye has been attributed to elevated insoluble arabinoxylan concentrations as well (Antoniou and Marquardt, 1981). Alkylresorcinols in rye may be responsible for poor taste, but concentrations of alkylresorcinols are variable among cereal grain sources (Nyström et al., 2008). Although breeding techniques have been used to reduce levels of alkylresorcinols, it is no longer a primary breeding goal (Schwarz et al., 2016). Few scientific studies have evaluated the feed preferences in pigs with diets containing rye. When rye was included in a diet at 30% inclusion rate, it was preferred 45% of the time over a basal diet based on white rice, indicating no difference in feed preference in the 2-way comparison (Solà-Oriol et al., 2009). In the same study, when rye was included at 60% inclusion rate, it was preferred 29% of the time over the basal diet, indicating a preference for the basal diet; yet, when rye was fed as 100% of the diet, it was preferred 49% of the time over the basal diet. More research is needed to elucidate the true feeding preferences of pigs when rye is included in diets.

In addition to ergot alkaloids, mycotoxins, and alkylresorcinols, other anti-nutritional factors are present in rye that have limited its use in diets for pigs and poultry. Rye contains more trypsin inhibitors than barley, wheat, and oats, but less than soybeans (Sosulski et al., 1988; Herkelman et al., 1992; Schwarz et al., 2015). Trypsin inhibitors have negative effects on animal performance, however, newer hybrids of rye are claimed to have reduced trypsin inhibitor activity compared with older cultivars of rye (Schwarz et al., 2015).

Marquardt et al. (1979) and Antoniou et al. (1980) identified that the major anti-nutritional factor in rye is likely a polysaccharide. Insoluble and soluble pentosans, primarily consisting of xylose and arabinose, were later identified as the main cause for growth depression in broiler chickens fed rye (Antoniou et al., 1981). The likely mechanism for reduced growth performance was two-fold. First, the broilers demonstrated reduced feed intake, which may have been caused by increased swelling of fiber in the digestive tract. Secondly, the broilers may have experienced decreased digestibility of nutrients because of increased digesta viscosity and reduced enzyme activity as a result of the arabinoxylans in rye (Antoniou et al., 1981).

Pigs are less sensitive than poultry to changes in digesta viscosity; therefore, soluble arabinoxylans appear to have a limited effect on digestibility and enzyme activity in pigs (Thacker et al., 1991; Zuber et al., 2016), and no difference on growth performance parameters were observed when pigs were fed diets containing low- or high-viscosity rye (Thacker et al., 2002). Increased digesta viscosity may reduce protein and lipid digestibility as a result of increased endogenous protein loss and decreased lipid absorption, respectively (Larsen et al., 1993; Bach Knudsen et al., 2005). Insoluble arabinoxylans also present an obstacle for nutrient digestibility and growth performance in pigs fed rye because the fiber in rye entraps nutrients and reduces enzymatic digestion and absorption (Annison and Choct, 1991; Bach Knudsen, 2014). Despite being disadvantageous to pigs, a high concentration of arabinoxylans in rye is desirable for bread because it improves dough quality (Buksa et al., 2010). Therefore, if the flour industry remains the driving force for genetic development of rye, it is unlikely the concentration of arabinoxylans will be reduced in future rye hybrids (Geiger and Miedaner, 2009; Jürgens et al., 2012).

CONCLUSION

The nutritional characteristics of rye indicate that rye contains more fiber than other cereal grains, including wheat and corn. Rye contains approximately 12% CP, but hybrid rye contains less. Like other cereal grains, rye has very limited concentrations of Ca, and approximately 0.4% P. As a feed ingredient, rye provides energy to the pig mostly via digestion of starch and fermentation of fiber. Thus far, limited research has been conducted to evaluate the efficacy of feeding hybrid rye to pigs. Hybrid rye only recently became commercially available in the U.S., therefore, production is still limited. However, its agronomic advantages, including high yield potential and abiotic stress tolerance, may result in more producers choosing to plant the crop in North America.

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CHAPTER 3: THE CONCENTRATION OF STANDARDIZED ILEAL DIGESTIBLE AMINO ACIDS IN HYBRID RYE IS NOT DIFFERENT FROM CORN ALTHOUGH DIGESTIBILITY OF AMINO ACIDS IN HYRID RYE IS LESS THAN IN OTHER CEREAL GRAINS

ABSTRACT

An experiment was conducted to determine the apparent ileal digestibility (AID) of AA and starch and the standardized ileal digestibility (SID) of AA in 3 varieties of hybrid rye and in one source of barley, wheat, and corn. Seven growing barrows (initial BW = 26.1 ± 2.4 kg) were randomly allotted to a 7 × 7 Latin square design with 7 periods and 7 experimental diets. Six diets included one of the cereal grains as the sole source of AA, and a N-free diet was used to determine basal endogenous losses of CP and AA. In each period, ileal digesta were collected for 8 hours on d 6 and 7 following a 5-d adaptation period. At the conclusion of the experiment, all ingredients, diets, and ileal digesta samples were analyzed for starch, CP, and AA. The AID of starch was greater ($P < 0.05$) in wheat and corn than in barley or hybrid rye, but all grains had AID values for starch that were above 95%. Wheat and barley contained more CP and indispensable AA than hybrid rye, but hybrid rye contained more indispensable AA compared with corn. The SID of CP and all indispensable AA was greater ($P < 0.05$) in barley, wheat, and corn than in the 3 varieties of rye. However, because of the greater concentration of AA in hybrid rye than in corn, the quantities of standardized ileal digestible CP and AA were not different between corn and hybrid rye. In conclusion, hybrid rye has greater concentrations of most AA than corn, but the digestibility of AA in rye is less than in other cereal grains. It is likely that the reason for the reduced SID of AA in rye is that rye contains more

fructooligosaccharides and soluble dietary fiber than other cereal grains, which may increase viscosity and reduce the efficiency of endogenous peptidases.

Key words: amino acid digestibility, cereal grains, hybrid rye, pigs, starch digestibility

INTRODUCTION

Rye has traditionally not been included in diets fed to pigs in great amounts because most rye in the world is grown for human consumption and primarily used by the grain flour industry for bread making (Bengtsson et al., 1992). Old varieties of rye were sometimes contaminated by ergot, which prevented usage of large quantities in diets fed to pigs (Friend and Macintyre, 1970). However, with the advent of hybrid rye and the Pollen Plus technology (KWS Lochow GmbH, Bergen, Germany), which utilizes the *Rfp1* and *Rfp2* restorer genes, the risk of ergot contamination has been reduced (Hackauf et al., 2012; Miedaner and Geiger, 2015).

Rye has high concentrations of non-starch polysaccharides, which have been correlated with anti-nutritive properties, especially in young pigs and poultry (Jürgens et al., 2012). However, the fructooligosaccharides in rye are easily fermentable and will, therefore, provide energy for the pig via fermentation in the hindgut. Likewise, the non-starch polysaccharides in rye may promote greater butyrate production and improve intestinal health (Bach Knudsen et al., 2005; 2016; 2017), and rye may, therefore, have prebiotic effects if included in diets for pigs.

Historically, production of rye has taken place mainly in northern European countries and production in the Americas has been limited. However, because hybrid rye has greater yields than other small grains including conventional rye in Europe, it is likely that hybrid rye can also out-yield other small grains such as sorghum, wheat, and barley on the drier soils in the U.S. and Canada (Jürgens et al., 2012). This may make hybrid rye an interesting ingredient in the feeding of pigs and other livestock species, but at this point, there is limited information about the nutritional value of hybrid rye when fed to pigs. It was, therefore, the objective of this experiment to test the hypothesis that hybrid rye, due to its improved chemical composition, provides ileal digestible quantities of starch, CP, and AA that are comparable to values obtained in barley, wheat, and corn.

MATERIALS AND METHODS

The experiment was conducted at the Swine Research Center at the University of Illinois following a protocol that was approved by the Institutional Animal Care and Use Committee at the University of Illinois.

Animals, Housing, and Experimental Design

Seven growing barrows (initital BW = 26.1 ± 2.4 kg) that were the offspring of Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN) were prepared with a cannula in the distal ileum as previously described (Stein et al., 1998). Pigs were housed in individual pens equipped with a tri-bar slatted floor, a feeder, and a nipple waterer. Following a 7-d recovery period from the surgery, animals were allotted to a 7 × 7 Latin square design with 7 periods and 7 animals. Animals were assigned to experimental diets in such a way that each diet was fed to only one pig in each period. There were, therefore, a total of 7 diets and 7 replicate observations per diet.

Three hybrids of rye (KWS Lochow GmbH, Bergen, Germany) and one source of dehulled barley, wheat, and corn were used in the experiment. All of the cereal grains used in the experiment were grown in 2016. Two of the hybrids of rye were grown in Germany, and one of the hybrids of rye was grown in Canada. The barley, wheat, and corn used in the experiment were grown in the U.S. Grains were ground using a hammer mill to a mean particle size of approximately 300 μm, and each grain was used in one diet. Thus, 3 diets containing hybrid rye and one diet containing barley, one diet containing wheat, and one diet containing corn were formulated (Tables 3.1 and 3.2). Each diet contained 94% grain as the sole source of starch and AA. Diets also contained 3% soybean oil, and 0.4% chromic oxide was used as an indigestible marker. Vitamins and minerals were included according to estimated nutrient requirements for growing pigs (NRC, 2012). A N-free diet based on cornstarch and sucrose was also included in the experiment to determine basal endogenous losses of CP and AA.

Feeding and Sample Collection

Feed was provided daily to each pig at the equivalence of 3.2 times the estimated requirement for ME for maintenance (i.e., 197 kcal ME per kg $BW^{0.60}$; NRC, 2012), and water was available at all times. The BW of each pig was recorded at the beginning and at the end of each period. Each period lasted 7 d, with the initial 5 d being an adaptation period to the diets, and ileal digesta were collected for 8 h on d 6 and 7 as previously described (Stein et al., 1998). All ileal digesta samples were stored at -20 ºC immediately after collection.

Chemical Analyses

At the conclusion of each period, ileal digesta samples were mixed within pig and a subsample was collected, lyophilized, and finely ground. The chromium concentration was determined in diets and ileal digesta samples using the Inductive Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int., 2007). Samples were prepared for analysis using nitric acid-perchloric acid (method 968.08D (b); AOAC Int., 2007). Crude protein was determined in diets, ingredients, and ileal digesta samples by measuring N concentration using the Kjeldahl method (method 976.05; AOAC Int., 2007), and DM was determined by oven drying at 135 °C for 2 h (method 930.15; AOAC Int., 2007). These samples were also analyzed for AA on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for post-column derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110 °C (method 982.30 E[a]; AOAC Int., 2007). Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E[b]; AOAC Int., 2007). Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C (method 982.30 E[c]; AOAC Int., 2007). Total starch was analyzed by the glucoamylase procedure (method 979.10; AOAC Int., 2007), which yields the enzymatically hydrolyzed starch in the ingredients.

The GE of ingredient samples was measured using an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL). Benzoic acid was used as the standard for calibration. All grain samples were also analyzed for dry ash (method 942.05; AOAC Int., 2007), and total acid-hydrolyzed ether extract was analyzed by acid hydrolysis using 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). Acid detergent fiber and NDF were analyzed using Ankom Technology methods 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY). After ADF analysis, ADL was determined using Ankom Technology method 9 (Ankom Daisy II Incubator, Ankom Technology, Macedon, NY). Insoluble dietary fiber and soluble dietary fiber were analyzed according to method 991.43 (AOAC Int., 2007) using the Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Total dietary fiber was calculated as the sum of soluble dietary fiber and insoluble dietary fiber. Free monosaccharide and sucrose concentrations were determined by

HPLC following the procedure by Smiricky et al. (2002), and hydrolyzed monosaccharide concentrations were determined by HPLC following the procedure by Bourquin et al. (1990) and Hoebler et al. (1989) and corrected for free monosaccharides. The concentration of mixed-linked β-glucans was determined according to method 995.16 (AOAC Int., 2002). Ingredients were also analyzed for inulin by refractive index HPLC using a Phenomenex Rezex RHM column (Phenomenex, Inc., Torrance, CA) following a procedure by Campbell et al. (1997). Briefly, 1.0 g of sample was extracted at 85 °C for 15 min, cooled, and analyzed. The mobile phase for pure water had a flow rate of 0.6 mL/min.

Aspergillus and *fusarium* mycotoxin analysis on all cereal grains were performed at Trilogy Analytical Laboratories (Washington, MO) using liquid chromatography-tandem mass spectroscopy. Ergot alkaloids were analyzed by refractive index HPLC using Phenomenex Strata-X-CW (Phenomenex, Inc., Torrance, CA) weak cation exchange and reversed phase column.

Physical Characteristics

Ingredient samples were analyzed for bulk density following the procedure by Cromwell et al. (2000) by pouring each ingredient into a tared 250 mL beaker, leveling off the top, and recording the weight of the tared beaker. Particle size of ingredients was analyzed with a Ro-Tap Sieve Shaker (W.S. Tyler, Mentor, OH) with 13 sieves of sieve opening sizes 53 to 3,360 µm (procedure S319.4, ANSI/ASAE, 2008). Ingredients were analyzed for swelling capacity based on the bed volume technique described by Kuniak and Marchessault (1972) and Canibe and Bach Knudsen (2002). Viscosity of ingredient samples was measured using a procedure modified after Serena and Bach Knudsen (2006) and was expressed in mPa·s. Briefly, 2 g of sample was dissolved in 10 mL of 0.9% NaCl and 0.02% NaN_3 solution and extracted in a water bath at 40 °C for 1 h. The sample was then centrifuged at 3,500 × *g* for 25 min at 23 °C and 0.5 mL of the supernatant was removed by suction. Viscosity of the supernatant was measured using a Brookfield LV-DV-2T viscometer (Brookfield Eng. Lab. Inc., Middleboro, MA) with a Wells-Brookfield Cone/Plate extension and a CPA-40Z cone spindle over a range of shear rates from 30.00 to 52.50 s^{-1}. Viscosity of solutions was measured at room temperature (23 °C). Water binding capacity was analyzed in all ingredient samples following a modified procedure described by Robertson et al. (2000). In short, 3 g of sample was hydrated in 30 mL of 0.9% NaCl and 0.02% NaN_3 solution for 18 h at room temperature, and then centrifuged for 20 min at 3000 × *g*. The sample was weighed after the supernatant had been removed, and values for water binding capacity were recorded as g of water retained by the pellet (g per g of dry weight).

Calculations and Statistical Analysis

Apparent ileal digestibility (**AID**) values of AA in each diet were calculated using the following equation (Stein et al., 2007):

$$\mathrm{AID_{AA}}, \% = 100 - [\left(\frac{\mathrm{AA_{digesta}}}{\mathrm{AA_{feed}}}\right) \times \left(\frac{\mathrm{Cr_{feed}}}{\mathrm{Cr_{digesta}}}\right)] \times 100$$

where AID_{AA} is AID of an AA (%), $AA_{digesta}$ is the concentration of that AA in the ileal digesta (DM), AA_{feed} is the AA concentration of that AA in the feed (DM), Cr_{feed} is the chromium concentration in the feed (DM), and $Cr_{digesta}$ is the chromium concentration in the ileal digesta (DM). The AID of CP and starch were also calculated using this equation.

The basal endogenous flow of each AA to the distal ileum was determined based on the flow obtained after feeding the N-free diet using the following equation (Stein et al., 2007):

$$\mathrm{IAA_{end}} = [\mathrm{AA_{digesta}} \times \left(\frac{\mathrm{Cr_{feed}}}{\mathrm{Cr_{digesta}}}\right)]$$

where IAA_{end} is the basal ileal endogenous loss of an AA (mg per kg DM intake). The basal ileal endogenous loss of CP was determined using the same equation.

By correcting the AID for the IAA_{end} of each AA, standardized ileal digestibility (**SID**) values of AA were calculated using the following equation (Stein et al., 2007):

$$\mathrm{SID_{AA}} = [\frac{\mathrm{AID} + \mathrm{IAA_{end}}}{\mathrm{AA_{feed}}}]$$

where SID_{AA} is the SID value (%) of each AA. The SID for CP was calculated using the same equation. The concentrations of standardized ileal digestible CP and AA were calculated by multiplying the SID coefficient (%) by the respective CP and AA concentration in each cereal grain.

Data were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC). Outliers were detected using the ROBUSTREG procedure and were removed from further statistical analyses. An outlier was defined as a value with a standardized robust residual of greater than 3 or less than -3. The statistical model included source of grain as fixed effect and period and animal as random effects. The model was fitted with the restricted maximum likelihood (REML) method and the degrees of freedom were estimated using the Kenward-Rogers approach. Least squares means were estimated and separated using the PDIFF statement with Tukey-Kramer adjustment in PROC MIXED. The pig was the experimental unit for all analyses. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

RESULTS

All pigs recovered from surgery without complications, and generally consumed their diets throughout the experiment without apparent problems. Three observations were excluded from all statistical analyses due to statistical outliers being detected. Therefore, there were only 6 observations for one of the hybrid rye diets, for the wheat diet, and for the corn diet.

The GE among all grain samples ranged from 3,763 kcal/kg in one hybrid of rye to 3,874 kcal/kg in corn (Table 3.3). The CP was numerically lowest in corn with 7.20%, followed by rye with values of 8.65%, 9.08%, and 8.90%. The CP in barley and wheat was 10.54% and 11.35%, respectively. The concentration of starch ranged from 54.99% in one hybrid of rye to 63.22% in corn. The analyzed values for Lys were 0.36% in the 3 hybrid ryes, 0.39% in barley, 0.37% in wheat, and 0.27% in corn. The Met content was 0.15% in the 3 hybrid ryes and corn, and slightly greater in wheat and barley. Corn had the lowest concentration of Thr (0.27%), followed by hybrid rye (0.29 to 0.30%), barley (0.33%), and wheat (0.35%). The concentration of Trp was also least in corn, followed by hybrid rye, wheat, and barley.

All cereal grains had low concentrations of free monosaccharides with glucose being most abundant (Table 3.4). Rye had the greatest amount of hydrolyzed arabinose and xylose, ranging from 25.44 to 28.21 mg/g and 52.72 to 56.93 mg/g, respectively. Rye had a greater concentration of mixed-linked β-glucans than wheat and corn, but barley contained more mixed-linked β-glucans (4.36%) than all other grains. Rye had greater concentrations of inulin than barley, wheat, and corn.

All ingredient samples had undetectable concentrations of *aspergillus* and *fusarium* mycotoxins, with the exception of one hybrid of rye, wheat, and corn, which had 1.3, 6.1, and 0.7 mg/kg of deoxynivalenol, respectively (Table 3.5). The 3 hybrids of rye had small, but detectable, concentrations of ergot alkaloids, ranging from 10.3 to 444.3 µg/kg. All ingredients were ground using the same hammer mill, thus, bulk density and particle size were not different among ingredients (Table 3.6). The mean particle size ranged from 213.3 to 383.0 µm. The viscosity in the rye hybrids was numerically higher than in barley, wheat, and corn, and the water binding capacity ranged from 0.87 to 1.39 g of water per g dry weight in one source of rye and in barley, respectively.

The AID of CP, starch, and all AA did not differ among the 3 varieties of hybrid rye (Table 3.7). The AID of CP was greater ($P < 0.05$) in wheat and barley than in hybrid rye, but there was no difference among corn and 2 of the sources of hybrid rye. The AID of starch ranged from 95.0% in one source of rye to 98.4% in corn. The AID of starch was greater ($P < 0.05$) in wheat and corn than in hybrid rye and barley. The AID of most indispensable AA was greater ($P < 0.05$) in barley, wheat, and corn than in the 3 hybrids of rye. The AID of CP and most AA did not differ among barley, wheat, and corn. The AID of Leu was greater ($P < 0.05$) in corn than in barley, the AID of Ala was greater ($P < 0.05$) in corn than in barley and wheat, the AID of Cys was greater ($P < 0.05$) in barley and wheat than in corn, the AID of Glu was greater ($P < 0.05$) in wheat than in barley and corn, and the AID of Gly was greater ($P < 0.05$) in wheat than in corn. There was no difference between corn and at least one source of hybrid rye for the AID of Lys, Trp, Val, Cys, Glu, and Gly.

The SID of CP and all AA did not differ among sources of hybrid rye (Table 3.8). The SID of most indispensable AA was greater ($P < 0.05$) in barley, wheat, and corn than in the 3 hybrids of rye. There was no difference between one of the hybrids of rye, barley, and corn for the SID of Trp, nor was there a difference between one of the hybrid ryes and wheat for the SID of Val. The SID of Asp, Glu, Gly, and total AA did not differ between one of the hybrids of rye and barley. With the exception of Leu, Met, Thr, Ala, and Glu, the SID of CP and all AA did not differ among barley, wheat, and corn.

The concentration of standardized ileal digestible CP was greatest ($P < 0.05$) in wheat, followed by barley, hybrid rye, and corn (Table 3.9). For most AA, the concentrations of standardized ileal digestible AA were greater ($P < 0.05$) in barley and wheat than in corn and hybrid rye. The were no differences between corn and at least one hybrid of rye for most concentrations of standardized ileal digestible AA, but corn contained more standardized ileal digestible His, Leu, Met, Ala, and Tyr than hybrid rye. Likewise, at least one of the hybrids of rye contained more standardized ileal digestible CP, Trp, Cys, Glu, and total dispensable AA than corn. Differences ($P < 0.05$) were observed for the concentrations of standardized ileal digestible CP and 5 AA among the hybrids of rye.

DISCUSSION

Although rye has historically not been used extensively in animal feeding, hybrid rye has the potential to be cost-effective in comparison with other cereal grains when used in diets for pigs (Schwarz et al., 2015). Hybrid rye has several agronomic advantages over other small cereal grains and older rye cultivars, including superior drought tolerance, overwintering ability, and increased yield (Jürgens et al., 2012; Schittenhelm et al., 2013). In addition, current varieties of hybrid rye have reduced incidence of ergot (Miedaner and Geiger, 2015), which mitigates some of the risk previously associated with including rye in swine diets. In the U.S., rye is considered "ergoty" if it contains more than 0.3% ergot by weight (USDA, 2013), at which point the value may be reduced. In the present study, the concentrations of ergot in the 3 hybrid ryes were well below this threshold.

Another perceived limitation for including rye in swine diets is the prevalence of pentoses, which are considered to have anti-nutritional properties (Antoniou et al., 1981). In the present study, rye contained more hydrolyzed xylose and arabinose compared with barley, wheat, and corn. Xylose is the only sugar in the backbone of arabinoxylans, and arabinose is the main sugar in the side chains. Arabinoxylans are the main constituent of fiber in cereal grains and are indigestible by endogenous enzymes in monogastric animals. However, arabinoxylans will be partially fermented in the large intestine with subsequent synthesis and absorption of short-chain fatty acids, which will contribute energy to the pig. Likewise, fermentation of rye fiber in the hindgut will also increase the synthesis of butyrate by intestinal microbes and improve intestinal health (Bach Knudsen et al., 2005; 2016; 2017).

The concentration of starch in hybrid rye was in agreement with values reported by Strang et al. (2016) and Cervantes-Pahm et al. (2013), but the AID of starch in hybrid rye obtained in this experiment was greater than values reported by Lærke et al. (2015) and Cervantes-Pahm et al. (2013). Reducing the particle size of ground corn from 865 µm to 339 µm linearly increases the AID of starch (Rojas and Stein, 2015); thus, the relatively high AID of starch observed in this experiment may be due to the low average particle size of the cereal grains.

The CP and AA concentrations in the 3 hybrids of rye used in the experiment were lower than values in summarized feed tables as well as several other published reports (NRC, 2012; Brestensky et al., 2013; Cervantes-Pahm et al., 2013; 2014; Rodehutscord et al., 2016). However, concentrations of most AA in the rye used in the present experiment were in agreement with values by Strang et al. (2016) and by Evonik Industries (2016). The sample size reported by NRC (20120) for CP and AA in rye was small (n = 2), and there is often variation among cereal grain genotypes in concentrations of CP and AA (Zuber et al., 2016; Strang et al., 2016). Variation is particularly pronounced when comparing old cultivars with new cultivars

(Peltonen-Sainio et al., 2012), which may explain some of the discrepancies among published values.

The calculated SID of CP and AA in the 3 hybrids of rye used in the present experiment was also comparable to Strang et al. (2016) and Cervantes-Pahm et al. (2014), but was greater than values reported by Brestensky et al. (2013), and less than values from NRC (2012) and Evonik Industries (2016). Nevertheless, the concentrations of standardized ileal digestible Lys, Met, Thr, and Trp were in close agreement with Strang et al. (2016) and Evonik Industries (2016), but less than values reported by Cervantes-Pahm et al. (2014), Brestensky et al. (2013), and NRC (2012).

The concentrations of CP and AA in barley, wheat, and corn were comparable to previous data (NRC, 2012; Cervantes-Pahm et al., 2014; Stein et al., 2016). The SID of CP and AA in barley and corn was slightly greater in the present study than reported by NRC (2012), Cervantes-Pahm et al. (2014), and Stein et al. (2016), but the SID of CP and AA in wheat was comparable to values from Stein et al. (2016).

The reduced SID of CP and AA in rye compared with barley, wheat, and corn may be due to the greater concentration of total dietary fiber in rye. The observation that the 3 hybrid rye cultivars contained more fructooligosaccharides than barley, wheat, and corn, and more arabinose, xylose, and mixed-linked β-glucans than wheat and corn is in agreement with previous data (Rodehutscord et al., 2016). The values obtained for fructooligosaccharides and total dietary fiber in the present study vary slightly from Rodehutscord et al. (2016), however, the values obtained for rye are close to what was recently published by Strang et al. (2016). Greater concentrations of fructooligosaccharides and soluble dietary fiber have been associated with increased viscosity and reduced nutrient digestibility, particularly in poultry (Choct and

Annison, 1992; Annison, 1991). Due to disparate shear rates and shear stresses used to measure viscosity of digesta samples, comparing numeric values for viscosity among laboratories is not possible (Dikeman and Fahey, 2006). However, increased viscosity observed in rye compared with barley, wheat, and corn has been previously reported (Lázaro et al., 2003; Rodehutscord et al., 2016). It is possible that the combination of increased concentrations of soluble and insoluble non-starch polysaccharides in rye is the reason for the reduced SID of AA in rye compared with barley, wheat, and corn.

In conclusion, the AID and SID of most AA in hybrid rye were less than in barley, wheat, and corn, but concentrations of standardized ileal digestible CP and most AA in hybrid rye was greater than or comparable to concentrations in corn. Thus, the hybrid rye used in this experiment may replace corn in diets for pigs without changing the provision of digestible AA. Further research is warranted to determine the digestibility of energy and other nutrients and the appropriate inclusion rate of hybrid rye in diets for pigs at various stages of production.

TABLES

Table 3.1: Ingredient composition of experimental diets

Ingredient, %	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	N-free
Cereal grain	94.20	94.20	94.20	94.05	94.15	93.85	-
Cornstarch	-	-	-	-	-	-	68.00
Soybean oil	3.00	3.00	3.00	3.00	3.00	3.00	4.00
Limestone	1.00	1.00	1.00	0.80	1.05	0.60	0.40
Dicalcium phosphate	0.70	0.70	0.70	1.05	0.70	1.45	1.90
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40	0.40	0.40	0.40	0.50
Vitamin-mineral premix[1]	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Solka-floc[2]	-	-	-	-	-	-	4.00
Magnesium oxide	-	-	-	-	-	-	0.10
Potassium dioxide	-	-	-	-	-	-	0.40
Sucrose	-	-	-	-	-	-	20.00

[1]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

[2]International Fiber Corporation, North Tonawands, NY.

Table 3.2: Analyzed composition of experimental diets containing 3 sources of hybrid rye, barley, wheat, or corn, as-fed basis

Item, %	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	N-free
DM	88.32	88.29	89.07	89.19	89.66	88.94	93.83
CP	8.35	8.37	8.60	9.82	10.50	6.70	0.27
Starch	53.08	53.53	51.25	57.02	56.49	58.61	59.48
Indispensable AA							
Arg	0.40	0.41	0.43	0.46	0.51	0.32	0.01
His	0.19	0.19	0.19	0.22	0.24	0.20	ND[1]
Ile	0.29	0.30	0.31	0.37	0.37	0.25	0.02
Leu	0.53	0.52	0.54	0.68	0.68	0.77	0.03
Lys	0.32	0.33	0.33	0.37	0.34	0.23	0.01
Met	0.13	0.14	0.14	0.16	0.17	0.13	ND
Phe	0.39	0.39	0.41	0.53	0.47	0.34	0.02
Thr	0.27	0.27	0.28	0.33	0.31	0.25	0.01
Trp	0.07	0.09	0.07	0.10	0.11	0.06	<0.02
Val	0.40	0.40	0.42	0.50	0.48	0.33	0.01
Dispensable AA							
Ala	0.36	0.35	0.36	0.38	0.39	0.49	0.01
Asp	0.57	0.57	0.59	0.58	0.58	0.46	0.04
Cys	0.18	0.18	0.18	0.23	0.23	0.14	0.02
Glu	1.87	1.84	1.96	2.38	2.76	1.21	0.03
Gly	0.36	0.36	0.38	0.39	0.44	0.28	0.01
Pro	0.84	0.80	0.87	1.11	0.97	0.63	0.02
Ser	0.32	0.32	0.33	0.37	0.42	0.30	0.01
Tyr	0.18	0.18	0.18	0.26	0.25	0.20	0.01
Total AA	7.86	7.83	8.15	9.63	9.92	6.79	0.44

[1]ND = not detected.

Table 3.3: Analyzed composition of 3 sources of hybrid rye, barley, wheat, and corn, as-fed basis

Item	Rye 1	Rye 3	Rye 2	Barley	Wheat	Corn
GE, kcal/kg	3,763	3,772	3,797	3,829	3,867	3,874
DM, %	87.56	87.19	88.15	88.17	87.85	88.10
CP, %	8.65	8.90	9.08	10.54	11.35	7.20
Ash, %	1.48	1.46	1.55	1.34	1.76	1.21
AEE[1], %	1.75	1.72	1.58	1.76	3.75	2.54
ADF, %	2.46	2.52	2.84	1.33	2.84	2.03
NDF, %	13.99	13.99	15.05	10.20	11.21	8.76
ADL, %	0.64	0.61	0.76	0.18	0.82	0.27
Insoluble dietary fiber, %	13.31	13.08	14.67	9.63	10.63	10.11
Soluble dietary fiber, %	1.85	3.48	1.82	2.76	0.46	ND[2]
Total dietary fiber, %	15.16	16.56	16.49	12.80	11.10	10.11
Starch, %	56.21	54.99	55.19	59.72	60.49	63.22
Indispensable AA, %						
Arg	0.44	0.44	0.45	0.48	0.53	0.36
His	0.21	0.21	0.21	0.23	0.26	0.21
Ile	0.32	0.32	0.32	0.39	0.41	0.28
Leu	0.57	0.56	0.57	0.72	0.73	0.84
Lys	0.36	0.36	0.36	0.39	0.37	0.27
Met	0.15	0.15	0.15	0.17	0.18	0.15
Phe	0.42	0.42	0.44	0.56	0.50	0.37
Thr	0.29	0.29	0.30	0.35	0.33	0.27
Trp	0.08	0.10	0.09	0.12	0.11	0.06
Val	0.43	0.44	0.44	0.53	0.51	0.37
Total	3.27	3.29	3.33	3.94	3.93	3.18

Table 3.3 (cont.)

Item	Rye 1	Rye 3	Rye 2	Barley	Wheat	Corn
Dispensable AA, %						
Ala	0.39	0.38	0.38	0.40	0.43	0.53
Asp	0.63	0.63	0.63	0.61	0.63	0.52
Cys	0.21	0.20	0.21	0.25	0.27	0.17
Glu	1.99	2.04	2.12	2.54	2.95	1.32
Gly	0.39	0.40	0.39	0.40	0.48	0.30
Pro	0.89	0.88	0.94	1.20	1.00	0.68
Ser	0.36	0.36	0.37	0.40	0.45	0.34
Tyr	0.20	0.19	0.20	0.27	0.26	0.23
Total	5.06	5.08	5.24	6.07	6.47	4.09
Total AA, %	8.52	8.57	8.75	10.21	10.60	7.41

[1]AEE = acid hydrolyzed ether extract.

[2]ND = not detected.

Table 3.4: Analyzed carbohydrate composition of 3 sources of hybrid rye, barley, wheat, and corn, DM basis[1]

Item	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn
Free sugars, µg/g						
Fucose	12.7	15.0	14.4	ND[2]	ND	ND
Arabinose	53.0	75.9	69.2	38.4	59.3	25.6
Galactose	63.4	70.8	51.0	122.5	82.0	84.9
Glucose	2,674.8	1,676.5	2,508.2	1,132.6	1,561.0	3,480.5
Xylose	310.2	300.4	360.3	164.7	217.4	179.5
Mannose	49.4	43.6	ND	39.8	47.0	ND
Fructose	912.7	1002.6	725.2	841.6	539.1	1,546.9
Hydrolyzed sugars, mg/g						
Arabinose	26.2	25.4	28.2	9.1	17.8	10.0
Galactose	10.9	10.3	10.7	7.8	11.2	10.1
Glucose	786.7	781.7	787.4	833.2	764.9	848.0
Xylose	52.7	56.9	56.2	24.0	44.6	23.6
Arabinose:Xylose	0.5	0.5	0.5	0.4	0.4	0.4
β-glucans, %	2.0	2.1	2.1	4.4	0.8	0.2
Fructans[3], %	1.4	1.1	1.4	0.5	0.2	0.1
Sucrose, %	1.2	1.3	1.5	0.8	0.8	0.9

[1]Total galacturonic and glucouronic acid in all ingredients were analyzed, but not detected.

[2]ND = not detected.

[3]Fructan content was determined by inulin analysis.

Table 3.5: Mycotoxin content of 3 sources of hybrid rye, barley, wheat, and corn, DM basis

Toxin	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn
Aspergillus						
Aflatoxin B1, µg/kg	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
Aflatoxin B2, µg/kg	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
Aflatoxin, G1, µg/kg	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
Aflatoxin G2, µg/kg	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
Fusarium						
Deoxynivalenol, mg/kg	<0.1	1.3	<0.1	<0.1	6.1	0.7
3-acetyl DON[1], mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
15-acetyl DON[1], mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
T-2, mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zearalenone, mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ergot alkaloids, µg/kg	444.3	10.3	10.4	-	-	-

[1]DON = deoxynivalenol.

Table 3.6: Physical characteristics of 3 sources of hybrid rye, barley, wheat, and corn, as-fed basis unless otherwise noted

Item	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn
Bulk density, g/L	615.4	614.5	620.5	653.1	597.8	579.9
Particle size, µm	287.7	383.0	351.1	373.4	213.3	237.0
Swelling, mL/g dry weight	3.8	3.4	3.2	3.5	2.9	2.8
Viscosity, mPa·s	2.2	2.5	2.3	1.5	1.2	1.5
WBC[1], g water/g dry weight	1.2	0.9	1.1	1.4	1.1	1.1

[1]WBC = water binding capacity.

Table 3.7: Apparent ileal digestibility (AID) of CP, starch, and AA in 3 sources of hybrid rye, barley, wheat, and corn

AID, %	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	SEM	*P*-value
CP	57.9^{c}	59.3^{bc}	62.8^{bc}	72.2^{a}	75.7^{a}	67.4^{ab}	2.12	<0.001
Starch	95.1^{b}	95.0^{b}	95.4^{b}	95.8^{b}	97.6^{a}	98.4^{a}	0.47	<0.001
Indispensable AA								
Arg	67.1^{b}	70.2^{b}	72.0^{b}	79.7^{a}	83.7^{a}	81.9^{a}	1.86	<0.001
His	67.4^{b}	66.6^{b}	67.9^{b}	79.0^{a}	82.7^{a}	81.0^{a}	1.67	<0.001
Ile	60.0^{b}	64.2^{b}	66.0^{b}	75.6^{a}	78.3^{a}	74.9^{a}	1.71	<0.001
Leu	65.3^{c}	64.0^{c}	69.3^{c}	78.7^{b}	81.1^{ab}	86.0^{a}	1.60	<0.001
Lys	52.1^{c}	51.2^{c}	57.6^{bc}	68.6^{a}	69.7^{a}	64.4^{ab}	2.49	<0.001
Met	69.8^{b}	72.2^{b}	73.2^{b}	80.2^{a}	84.2^{a}	84.3^{a}	1.23	<0.001
Phe	69.5^{b}	69.4^{b}	72.7^{b}	81.3^{a}	82.5^{a}	81.0^{a}	1.47	<0.001
Thr	44.9^{b}	43.7^{b}	52.0^{b}	65.3^{a}	63.5^{a}	61.3^{a}	2.37	<0.001
Trp	58.9^{c}	66.4^{bc}	66.7^{bc}	78.9^{a}	81.4^{a}	74.0^{ab}	2.36	<0.001
Val	56.3^{c}	54.5^{c}	61.2^{bc}	72.7^{a}	70.1^{a}	68.2^{ab}	1.98	<0.001
Total	61.3^{b}	61.5^{b}	65.7^{b}	76.3^{a}	77.6^{a}	77.4^{a}	1.77	<0.001
Dispensable AA								
Ala	50.2^{c}	51.3^{c}	54.4^{c}	65.0^{b}	64.8^{b}	78.6^{a}	2.46	<0.001
Asp	57.9^{c}	55.9^{c}	62.6^{bc}	68.1^{ab}	70.2^{a}	71.5^{a}	2.39	<0.001
Cys	63.9^{c}	66.2^{bc}	66.4^{bc}	79.8^{a}	79.7^{a}	71.3^{b}	1.37	<0.001
Glu	81.1^{c}	81.2^{c}	83.0^{bc}	86.4^{b}	91.7^{a}	84.7^{bc}	1.04	<0.001
Gly	30.0^{d}	37.0^{d}	42.0^{cd}	55.8^{ab}	65.2^{a}	51.1^{bc}	4.35	<0.001
Ser	60.7^{b}	60.7^{b}	65.1^{b}	74.2^{a}	77.9^{a}	74.4^{a}	1.86	<0.001
Tyr	60.2^{b}	60.4^{b}	61.8^{b}	76.4^{a}	77.7^{a}	74.9^{a}	1.29	<0.001
Total	68.3^{c}	70.5^{c}	72.2^{bc}	78.2^{ab}	84.2^{a}	73.4^{bc}	1.93	<0.001
Total AA, %	64.7^{c}	65.8^{c}	68.9^{bc}	77.3^{a}	80.9^{a}	75.3^{ab}	1.94	<0.001

$^{a\text{-}d}$Means in a row without a common superscript differ ($P < 0.05$).

Table 3.8: Standardized ileal digestibility (SID) of CP and AA in 3 sources of hybrid rye, barley, wheat, and corn[1]

SID, %	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	SEM	*P*-value
CP	75.2^{c}	76.4^{c}	79.7^{bc}	87.1^{ab}	89.5^{a}	89.2^{a}	2.12	<0.001
Indispensable AA								
Arg	79.3^{b}	82.1^{b}	83.3^{b}	90.4^{a}	93.4^{a}	97.2^{a}	1.86	<0.001
His	75.6^{b}	74.8^{b}	76.2^{b}	86.2^{a}	89.4^{a}	88.8^{a}	1.67	<0.001
Ile	71.7^{b}	74.5^{b}	76.1^{b}	84.1^{a}	86.9^{a}	87.4^{a}	1.71	<0.001
Leu	74.2^{c}	73.1^{c}	77.2^{c}	85.8^{b}	88.2^{ab}	92.2^{a}	1.60	<0.001
Lys	62.1^{b}	60.9^{b}	67.4^{b}	77.3^{a}	79.3^{a}	78.4^{a}	2.49	<0.001
Met	76.4^{c}	78.3^{c}	79.4^{c}	85.6^{b}	89.3^{ab}	90.9^{a}	1.23	<0.001
Phe	77.4^{b}	77.2^{b}	80.2^{b}	87.1^{a}	89.0^{a}	90.0^{a}	1.45	<0.001
Thr	64.0^{b}	62.8^{b}	70.6^{b}	81.0^{a}	80.4^{a}	82.1^{a}	2.37	<0.001
Trp	71.6^{c}	76.2^{c}	79.5^{bc}	87.8^{ab}	89.6^{a}	88.9^{ab}	2.36	<0.001
Val	69.9^{c}	68.1^{c}	74.3^{bc}	83.7^{a}	81.6^{ab}	84.8^{a}	1.98	<0.001
Total	72.4^{b}	72.4^{b}	76.5^{b}	85.3^{a}	86.7^{a}	89.0^{a}	1.77	<0.001
Dispensable AA								
Ala	65.6^{c}	67.2^{c}	70.0^{c}	79.8^{b}	79.2^{b}	90.0^{a}	2.46	<0.001
Asp	68.8^{c}	66.8^{c}	73.2^{bc}	78.9^{ab}	81.0^{a}	85.0^{a}	2.39	<0.001
Cys	73.6^{b}	75.8^{b}	76.1^{b}	87.4^{a}	87.3^{a}	83.8^{a}	1.37	<0.001
Glu	85.6^{d}	85.7^{d}	87.3^{cd}	90.0^{bc}	94.9^{a}	91.7^{ab}	1.04	<0.001
Gly	67.5^{c}	74.5^{c}	77.8^{bc}	90.8^{ab}	96.4^{a}	91.7^{a}	4.35	<0.001
Ser	74.3^{b}	74.4^{b}	78.5^{b}	86.2^{a}	88.5^{a}	89.1^{a}	1.86	<0.001
Tyr	73.1^{b}	73.3^{b}	74.8^{b}	85.4^{a}	87.1^{a}	86.6^{a}	1.29	<0.001
Total	87.4^{c}	89.9^{bc}	90.8^{bc}	93.9^{ab}	99.1^{a}	99.3^{a}	2.07	<0.001
Total AA	80.6^{c}	81.7^{c}	84.2^{bc}	90.3^{ab}	93.5^{a}	94.1^{a}	1.93	<0.001

[a-d]Means in a row without a common superscript differ ($P < 0.05$).

[1]Values for SID were calculated by correcting the values for apparent ileal digestibility for basal ileal endogenous losses. Basal endogenous losses were determined (g/kg of DM intake) as CP, 16.39; Arg, 0.55; His, 0.55; Iso, 0.18; Leu, 0.35; Lys, 0.54; Met, 0.36; Phe, 0.10; Thr, 0.35; Trp, 0.58; Val, 0.10; Ala, 0.62; Asp, 0.63; Cys, 0.70; Glu, 0.20; Gly, 0.96; Pro, 1.53; Ser, 5.15; and Tyr, 0.50.

Table 3.9: Concentrations (g/kg) of standardized ileal digestible CP and AA in 3 sources of hybrid rye, barley, wheat, and corn[1]

Item, g/kg	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	SEM	*P*-value
CP	65.1^{d}	68.0^{cd}	72.4^{c}	91.8^{b}	101.7^{a}	64.3^{d}	1.94	<0.001
Indispensable AA								
Arg	3.5^{d}	3.6^{cd}	3.8^{c}	4.3^{b}	5.0^{a}	3.5^{cd}	0.08	<0.001
His	1.6^{c}	1.6^{c}	1.6^{c}	2.0^{b}	2.3^{a}	1.9^{b}	0.04	<0.001
Ile	2.3^{c}	2.4^{c}	2.4^{c}	3.3^{b}	3.6^{a}	2.5^{c}	0.06	<0.001
Leu	4.2^{c}	4.1^{c}	4.4^{c}	6.2^{b}	6.4^{b}	7.7^{a}	0.10	<0.001
Lys	2.2^{b}	2.2^{b}	2.4^{b}	3.0^{a}	2.9^{a}	2.1^{b}	0.09	<0.001
Met	1.1^{c}	1.2^{c}	1.2^{c}	1.4^{b}	1.6^{a}	1.4^{b}	0.02	<0.001
Phe	3.3^{cd}	3.2^{d}	3.5^{c}	4.9^{a}	4.5^{b}	3.3^{cd}	0.07	<0.001
Thr	1.9^{cd}	1.8^{d}	2.1^{bc}	2.8^{a}	2.6^{a}	2.2^{b}	0.07	<0.001
Trp	0.6^{c}	0.7^{b}	0.7^{b}	1.0^{a}	1.0^{a}	0.5^{c}	0.03	<0.001
Val	3.0^{b}	3.0^{b}	3.3^{b}	4.4^{a}	4.2^{a}	3.1^{b}	0.09	<0.001
Total	23.7^{c}	23.8^{c}	25.5^{c}	33.6^{a}	34.1^{a}	28.3^{b}	0.60	<0.001
Dispensable AA								
Ala	2.6^{c}	2.6^{c}	2.6^{c}	3.2^{b}	3.4^{b}	4.8^{a}	0.10	<0.001
Asp	4.3^{c}	4.2^{c}	4.6^{bc}	4.8^{ab}	5.1^{a}	4.4^{bc}	0.15	<0.001
Cys	1.5^{cd}	1.5^{cd}	1.6^{c}	2.2^{b}	2.4^{a}	1.4^{d}	0.03	<0.001
Glu	17.0^{d}	17.5^{d}	18.5^{c}	22.8^{b}	28.0^{a}	12.1^{e}	0.22	<0.001
Gly	2.6^{c}	3.0^{c}	3.0^{c}	3.7^{b}	4.6^{a}	3.0^{c}	0.17	<0.001
Ser	2.7^{d}	2.7^{d}	2.9^{cd}	3.5^{b}	4.0^{a}	3.1^{c}	0.07	<0.001
Tyr	1.5^{c}	1.4^{c}	1.5^{c}	2.3^{a}	2.3^{a}	2.0^{b}	0.03	<0.001
Total	44.2^{d}	45.7^{cd}	47.6^{c}	57.0^{b}	64.1^{a}	40.6^{e}	0.98	<0.001
Total AA	68.6^{c}	70.0^{c}	73.7^{c}	92.2^{b}	99.2^{a}	69.7^{c}	1.71	<0.001

$^{a-e}$Means in a row without a common superscript differ ($P < 0.05$).

[1]Concentrations of standardized ileal digestible CP and AA were calculated by multiplying coefficients for the standardized ileal digestibility (%) of CP and AA by the respective concentration of CP and AA in each cereal grain.

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CHAPTER 4: MICROBIAL PHYTASE IMPROVES THE STANDARDIZED TOTAL TRACT DIGESTIBILITY OF PHOSPHORUS IN HYBRID RYE, BARLEY, WHEAT, CORN, AND SORGHUM FED TO GROWING PIGS

ABSTRACT

An experiment was conducted to determine the apparent total tract digestibility (ATTD) and the standardized total tract digestibility (STTD) of P in 3 varieties of hybrid rye and in one source of barley, wheat, corn, and sorghum. The STTD of P in each cereal grain was determined both without and with addition of microbial phytase. One hundred twelve growing barrows (initial BW = 13.7 ± 1.3 kg) were allotted to a randomized complete block design with 4 blocks of 28 pigs. Pigs were randomly allotted to 14 diets with 2 replicate pigs per diet in each block, resulting in a total of 8 replicate pigs per diet for the 4 blocks. Each diet contained one of the cereal grains as the sole source of P. There were 2 diets with each cereal grain with one diet containing no microbial phytase and the other diet containing 1,000 units of microbial phytase per kg of diet. In each period, fecal output was collected for 5 d following a 5-d adaptation period according to the marker-to-marker procedure. Among the diets that did not include microbial phytase, one hybrid of rye had greater ($P < 0.05$) STTD of P than wheat, corn, and sorghum, which is likely a result of the greater intrinsic phytase activity in rye than in the other cereal grains. Without microbial phytase, there was no difference in the STTD of P in the 3 hybrids of rye and barley. Among the diets containing microbial phytase, there was no difference in STTD of P among the 3 hybrids of rye, barley, and corn. The STTD of P in the 3 hybrids of rye with microbial phytase was 61.9%, 70.8%, and 63.0%, respectively. Overall, microbial

phytase improved (P < 0.05) the STTD of P in all cereal grains, although the magnitude of the increase in STTD of P differed among the grains.

Key words: calcium, cereal grains, digestibility, hybrid rye, pigs, phosphorus

INTRODUCTION

Rye is primarily grown in Europe for the bread-making, biogas, beverage, and livestock feed industries. Recently, hybrid varieties of rye from Europe became commercially available in North America, and compared with conventional rye, hybrid rye has increased crop yield and reduced risk of ergot contamination (Jürgens et al., 2012; Miedaner and Geiger, 2015), which makes hybrid rye more suitable for livestock feed than older cultivars of rye. However, there is limited data for the nutritional value of hybrid rye when fed to pigs. Previous research with hybrid rye has focused on the digestibility of AA (Strang et al., 2016; McGhee and Stein, 2018), but to our knowledge, there are no published data for the digestibility of P in pigs fed hybrid rye.

Cereal grains have a high percentage of total P bound to phytic acid (Nelson et al., 1968), which is not digested well by pigs, but addition of microbial phytase to diets increases the digestibility of P (Maga, 1982). Rye has high levels of intrinsic phytase (Rodehutscord et al., 2016), which may result in increased digestibility of P by pigs (Pointillart et al., 1987). It is, therefore, possible that the response to microbial phytase in hybrid rye is different from other cereal grains, but this hypothesis has not been experimentally tested. The objective of this experiment, therefore, was to test the hypothesis that the apparent total tract digestibility (**ATTD**) and the standardized total tract digestibility (**STTD**) of P in hybrid rye is greater than in barley, wheat, corn, and sorghum, and that addition of microbial phytase increases the ATTD and STTD of P in all cereal grains.

MATERIALS AND METHODS

The experiment was conducted at the Swine Research Center at the University of Illinois following a protocol that was approved by the Institutional Animal Care and Use Committee at the University of Illinois.

Animals, Housing, and Experimental Design

Three hybrids of rye (KWS Lochow GmbH, Bergen, Germany) and one source of dehulled barley, wheat, corn, and sorghum, all of which were grown in 2016, were used in the experiment. The 3 hybrids of rye included 2 hybrids that were grown in Germany and one hybrid that was grown in Canada. The barley, wheat, corn, and sorghum used in the experiment were grown in the U.S. Grains were ground using a hammer mill to a mean particle size of approximately 300 μm, and each grain was used in 2 diets. Seven diets contained each hybrid of rye or barley, wheat, corn, or sorghum in addition to sucrose, soybean oil, vitamins, and minerals (Table 4.1). No inorganic P was added to the diets, and all P in the diets, therefore, originated from the cereal grains. Limestone was included in each diet to maintain an overall Ca concentration of 0.4%. Seven additional diets that were similar to the initial 7 diets with the exception that they contained 1,000 units of microbial phytase (Quantum Blue 5G; AB Vista, Marlborough, UK) per kg of diet were also formulated.

One hundred twelve growing barrows (initial BW = 13.7 ± 1.3 kg) that were the offspring of Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN) were allotted to a randomized complete block design with 4 blocks of 28 pigs. Within each block, the 28 pigs were randomly allotted to the 14 diets with 2 replicate pigs per diet, resulting in a total of 8 replicate pigs per diet for the 4 blocks. Pigs were housed in individual metabolism crates that were equipped with a feeder, a nipple waterer, and fully slatted metal floors. A screen floor was placed under the slatted floor to allow for the total collection of fecal materials.

Feeding and Sample Collection

Pigs were fed at 3.0 times the estimated ME requirement for maintenance (i.e., 197 kcal ME per kg $BW^{0.60}$; NRC, 2012), which was provided each day in 2 equal meals at 0800 and 1600 h. Water was available on an *ad libitum* basis. Feed consumption was recorded daily and pigs were fed experimental diets for 12 d, with the initial 5 d being an adaptation period to the diets, and the following 5 d being used for total collection of feces according to the marker-to-marker procedure (Adeola, 2001).

Chemical Analyses

Fecal samples were stored at -20 °C immediately after collection. At the conclusion of the experiment, fecal samples were dried in a forced air oven and ground using a 1-mm screen in a Wiley mill (model 4, Thomas Scientific, Swedesboro, NJ). Samples of diets, ingredients, and fecal materials were analyzed for DM, Ca, and P. The DM of samples was determined by oven drying at 135 °C for 2 h (method 930.15; AOAC Int., 2007). Calcium and total P were measured by inductively coupled plasma - optical emission spectroscopy (method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation (method 975.03 B(b); AOAC Int., 2007). Ingredient samples were analyzed for Cu, K, Mg, Mn, and Zn using the same procedure, and concentrations of Fe, Na, and Se were also determined using inductively coupled plasma - optical emission spectroscopy (method 990.08; AOAC Int., 2007). The concentration of S was determined by gravimetric analysis (method 956.01; AOAC Int., 2007). The concentration of Cl was determined by manual titration (method 943.01; AOAC Int., 2007), and the concentration of I was determined by volumetric analysis (method 935.14; AOAC Int., 2007). Diet and ingredient samples were analyzed for dry ash (method 942.05; AOAC Int., 2007). The GE in diets was measured using an isoperibol bomb calorimeter (model 6400, Parr Instruments, Moline, IL). Benzoic acid was used as the standard for calibration. The CP in diets was determined by measuring N (method 990.03; AOAC Int., 2007) using a Leco Nitrogen Determinator (model FP628, Leco Corp., St. Joseph, MI). Diets and ingredients were analyzed for phytase activity (Phytex Method, Version 1; Eurofins, Des Moines, IA), and all ingredients were analyzed for phytic acid (Ellis et al., 1977). The phytic acid concentration in the diets was calculated using the phytic acid concentration in the ingredients. Phytate-bound P in diets and ingredients was calculated as 28.2% of phytic acid (Sauvant et al., 2004), and non-phytate P was calculated as total P (%) minus phytate-bound P (%).

Calculations and Statistical Analysis

The ATTD of P was calculated for each diet using the following equation (Almeida and Stein, 2010):

$$\text{ATTD (\%)} = \left[\frac{\mathrm{P}_i - P_f}{P_i}\right] \times 100$$

where P_i is the total P intake (g) from d 6 to 10 and P_f is the total fecal P output (g) originating from the feed that was provided from d 6 to 10. The same equation was used to calculate the ATTD of Ca.

The STTD of P was calculated using the following equation (NRC, 2012):

$$\text{STTD (\%)} = \left[\frac{\mathrm{P}_i - (P_f - EPL)}{P_i}\right] \times 100$$

where EPL is the basal endogenous loss of P. A basal endogenous loss of P of 190 mg per kg DM intake was assumed for all pigs (NRC, 2012), and this value was used to calculate the STTD of P in all diets.

Data were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC). The pig was the experimental unit for all analyses. An outlier was defined as an observation with a studentized residual of greater than 3 or less than -3 and was subsequently removed from further statistical analysis. PROC UNIVARIATE and PROC GPLOT were used to check model assumptions on the residuals. The model included ingredient source, level of phytase, and the interaction between ingredient and level of phytase as fixed effects and block and replicate within block as random effects. The model was fitted with the restricted maximum likelihood (REML) method and the degrees of freedom were estimated using the Kenward-Rogers approach. Least squares means were estimated and separated using the PDIFF statement with Tukey-Kramer adjustment in PROC MIXED. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

RESULTS

All pigs consumed their diets throughout the experiment without apparent problems. The GE in the diets ranged from 3,956 to 4,082 kcal/kg, and the CP in the diets ranged from 6.22% in one of the corn diets to 9.38% in one of the wheat diets (Table 4.2). The concentration of ash in the diets ranged from 2.34% to 2.96%, and the concentration of ash in the ingredients ranged from 1.21% to 1.76% (Table 4.3). Rye, barley, and wheat contained approximately 0.03% Ca, whereas both corn and sorghum contained 0.01% Ca. The concentration of total P was numerically greatest in wheat (0.36%) and numerically least in corn (0.23%). The 3 hybrids of rye contained 0.26%, 0.29%, and 0.32% total P. Barley contained the most non-phytate P (0.09%), followed by wheat, sorghum, and rye, which contained 0.06% to 0.08%, and corn contained only 0.04% non-phytate P. The 3 hybrids of rye had intrinsic phytase activities ranging from 2,300 to 3,200 phytase units per kg. In comparison, the intrinsic phytase activity of wheat and barley was 580 and 490 phytase units per kg, respectively, and corn and sorghum had less than 100 phytase units per kg intrinsic phytase activity.

There was no source by phytase interaction for ADFI nor fecal output (Table 4.4). There was no effect of microbial phytase on feed intake, but differences ($P < 0.05$) among cereal grains were observed. There was a tendency ($P < 0.10$) for pigs to have reduced fecal output if they were fed diets with microbial phytase compared with pigs fed diets without microbial phytase, and grain source also affected ($P < 0.05$) fecal output. There was no source by phytase interaction for P intake, and there was no effect of microbial phytase on P intake, however, differences ($P < 0.05$) in P intake among cereal grains were observed.

There were interactions ($P < 0.05$) between grain source and phytase for the concentration of P in feces, total P output, ATTD of P, and STTD of P, but all interactions were due to differences in the magnitude, rather than in the direction, of the response to phytase. With the exception of one source of hybrid rye, pigs fed diets containing microbial phytase had lower concentration of P in feces ($P < 0.05$) than pigs fed diets without microbial phytase. Total P output was reduced ($P < 0.05$) for one source of hybrid rye, and for barley, corn, and sorghum if microbial phytase was added to the diets. Among pigs fed diets without microbial phytase, pigs fed diets containing barley, wheat, corn, and sorghum had greater ($P < 0.05$) concentrations of P in feces than pigs fed the 3 hybrids of rye. If microbial phytase was added to the diets, pigs fed wheat also had greater concentration of P in feces ($P < 0.05$) than pigs fed any of the hybrids of rye.

The ATTD and STTD of P were greater ($P < 0.05$) in diets containing microbial phytase compared with diets without microbial phytase for all cereal grains. Among diets without microbial phytase, the STTD of P was greater ($P < 0.05$) in the 3 hybrids of rye than in corn and sorghum, and the STTD of P in one source of hybrid of rye was also greater ($P < 0.05$) than in wheat. There was no difference in ATTD or STTD of P between diets containing hybrid rye and the diet containing barley if no microbial phytase was used. For diets containing microbial phytase, there was no difference in ATTD and STTD of P among the 3 hybrids of rye, barley, or corn, but one source hybrid of rye had greater ($P < 0.05$) STTD of P than wheat and sorghum.

There was no grain source by phytase interaction, nor an effect of phytase, on daily Ca intake, but differences ($P < 0.05$) among grain sources were observed (Table 4.5). There were interactions ($P < 0.05$) for the concentration of Ca in feces, total fecal Ca output, and ATTD of Ca. The interactions were due to differences in the magnitude of the response to phytase among the grain sources. The concentration of Ca in feces was reduced ($P < 0.05$) when microbial phytase was added to the diets containing one source of hybrid of rye, barley, corn, or sorghum, and total daily output of Ca was also reduced ($P < 0.05$) when microbial phytase was added to the diets containing barley and corn. The ATTD of Ca was greater ($P < 0.05$) if microbial phytase was added to the diets containing one source of hybrid of rye, barley, wheat, corn, or sorghum. Among diets without microbial phytase, the ATTD of Ca was greater ($P < 0.05$) in 2 of the hybrids of rye compared with sorghum, and the ATTD of Ca in one source of hybrid of rye also resulted in greater ($P < 0.05$) ATTD of Ca than in corn. Among diets with microbial phytase, there was a greater ($P < 0.05$) ATTD of Ca in barley and one source of hybrid of rye than in sorghum.

DISCUSSION

Concentrations of P and phytate-bound P in rye were in agreement with published data (NRC, 2012; Nørgaard et al., 2016; Stein et al., 2016); however, Rodehutscord et al. (2016) reported slightly greater concentrations of P in rye than observed in the present study. The analyzed concentration of Ca in rye and barley was lower than reported values (NRC, 2012; Nørgaard et al., 2016; Rodehutscord et al., 2016; Stein et al., 2016). The concentration of Ca in wheat was in agreement with published values (NRC, 2012; Rodehutscord et al., 2016), but the concentrations of P and phytate-bound P were greater than reported by NRC (2012). In contrast, Rodehutscord et al. (2016) and Stein et al. (2016) reported concentrations of P in wheat that were very close to what was observed in the present study. Concentrations of Ca, P, and phytate-bound P in corn and sorghum were also in agreement with published data (Almeida and Stein, 2012; NRC, 2012; Rodehutscord et al, 2016; Stein et al., 2016; Pan et al., 2017).

Limited data for the STTD of P in rye are available, and to our knowledge, no data for STTD of P in hybrid rye have been published. However, values for STTD of P in rye that were observed in this experiment are generally in agreement with STTD values observed in older cultivars of rye (NRC, 2012; Stein et al., 2016). The ATTD of P in rye with microbial phytase is around 60% (Nørgaard et al., 2016), but we are not aware of data for the STTD of P in rye with microbial phytase. The observed STTD of P in barley without microbial phytase was very close to the value reported by NRC (2012), whereas the observed values for wheat, corn, and sorghum without microbial phytase were less than previously reported. The observed STTD of P in corn with microbial phytase was, however, close to previously published data (Almeida and Stein, 2012).

Most P is stored as phytic acid in cereal grains, which makes it mostly unavailable for absorption and utilization by pigs (Simons et al., 1990). Addition of microbial phytase to diets increases P availability (Maga, 1982) and total tract digestibility of P in pigs (Almeida and Stein, 2010; 2012), which was also observed in the present experiment. The greater STTD of P without microbial phytase in the rye hybrids compared with wheat, corn, and sorghum may be due to the greater intrinsic phytase activity in rye. Processing of feed at high temperature, such as steam pelletting, decreases the intrinsic phytase activity in wheat (Jongbloed and Kemme, 1990). Therefore, if the intrinsic phytase activity in rye is the reason for the greater STTD of P compared with other grains without microbial phytase, it is likely the greater digestibility will only be observed in rye-based diets that are not heat treated. However, we are not aware of published data for effects of heat treatment of rye on the STTD of P.

Without microbial phytase, the STTD of P was greater in hybrid rye than in corn, and when microbial phytase was added to the diets, there was no difference in STTD of P among the rye hybrids and corn. Therefore, regardless of whether microbial phytase is added to the diets, the provision of digestible P from hybrid rye is slightly greater than from corn because hybrid rye contains greater concentrations of total P. Thus, these data indicate that if hybrid rye replaces corn in diets, less inorganic P will be needed.

Values for the ATTD of Ca calculated in the present experiment primarily represent the digestibility of Ca in limestone because the contribution of Ca from the cereal grains was very low. The present results support the observation by González-Vega et al. (2015) that the ATTD and STTD of Ca in calcium carbonate increases with the addition of microbial phytase. The ATTD of Ca in limestone observed in this experiment was in agreement with reported values obtained in corn-based diets (Stein et al., 2011; González-Vega et al., 2015). There is, however, limited data for the ATTD of Ca in limestone or calcium carbonate obtained in diets based on other cereal grains. The effect of microbial phytase on the digestibility of Ca observed in the present study supports the hypothesis that dietary Ca from limestone binds to phytate in the intestinal tract of pigs, as described by González-Vega et al. (2015). The intrinsic phytase in the rye is likely the reason there was no increase in ATTD of Ca when microbial phytase was added to the diets based on 2 of the hybrids of rye, whereas for the other cereal grains that have less or no intrinsic phytase, addition of microbial phytase resulted in improved ATTD of Ca.

In summary, it is beneficial to include microbial phytase in swine diets that contain rye, barley, wheat, corn, or sorghum due to the increased STTD of P observed with microbial phytase supplementation. Without microbial phytase, one source of hybrid rye had greater STTD of P than wheat, corn, and sorghum, which supports the hypothesis that the digestibility of P is greater in hybrid rye than in other cereal grains because of the greater intrinsic phytase activity in rye. However, if microbial phytase was included in the diets, there were no differences in the STTD of P among the 3 hybrids of rye, and barley, and corn indicating that a certain level of phytase is needed to maximize STTD of P. Whether the phytase is of microbial origin or is intrinsic to the grain appers to be less important.

TABLES

Table 4.1: Ingredient composition of experimental diets[1]

Ingredient, %	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	Sorghum
Cereal grain	84.35	84.35	84.35	84.35	84.35	84.25	84.25
Sucrose	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Soybean oil	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Limestone	0.95	0.95	0.95	0.95	0.95	1.05	1.05
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30

[1]For each ingredient, an additional diet was prepared by including microbial phytase (Quantum Blue 5G; AB Vista, Marlborough, UK) at a level of 1,000 phytase units per kg diet (0.02%) at the expense of cereal grain. Thus, a total of 14 diets were prepared with the 7 ingredients.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Table 4.2: Composition of experimental diets containing 3 sources of hybrid rye, barley, wheat, corn, or sorghum, without or with microbial phytase, as-fed basis

Diet	DM, %	GE, kcal/kg	CP, %	Ash, %	Ca, %	P, %	Phytate[1], %	Phytate P[2], %	Non-phytate P[3], %	Phytase, FTU[4]
Without phytase										
Rye 1	90.24	3,956	7.36	2.69	0.42	0.24	0.60	0.17	0.11	1,900
Rye 2	90.18	3,976	7.75	2.87	0.43	0.27	0.66	0.19	0.10	1,300
Rye 3	90.64	3,972	7.79	2.80	0.43	0.30	0.74	0.21	0.10	2,200
Barley	91.26	4,015	8.42	2.64	0.44	0.26	0.54	0.15	0.12	270
Wheat	92.27	4,038	9.38	2.90	0.47	0.35	0.84	0.24	0.14	400
Corn	90.94	4,046	6.22	2.34	0.48	0.22	0.56	0.16	0.06	<70
Sorghum	90.80	4,082	8.32	2.63	0.42	0.24	0.62	0.17	0.07	<70
With phytase, 1,000 FTU										
Rye 1	90.47	3,975	7.65	2.93	0.41	0.22	0.60	0.17	0.09	3,100
Rye 2	90.26	3,973	7.71	2.96	0.43	0.26	0.66	0.19	0.08	3,000
Rye 3	90.89	3,967	8.01	2.88	0.41	0.28	0.74	0.21	0.10	3,700
Barley	92.02	4,031	8.89	2.57	0.39	0.24	0.54	0.15	0.11	1,700
Wheat	92.40	4,026	9.29	2.84	0.42	0.31	0.84	0.24	0.05	1,400
Corn	91.23	4,035	6.27	2.66	0.43	0.20	0.56	0.16	0.06	1,000
Sorghum	90.92	4,081	8.90	2.70	0.44	0.23	0.62	0.17	0.07	610

Table 4.2 (Cont.)

[1]Phytate concentration in the diets was calculated using the phytate concentration in the ingredients.

[2]Phytate-bound P was calculated as 28.2% of phytate (Sauvant et al., 2004).

[3]Non-phytate P was calculated as total P (%) minus phytate-bound P (%).

[4]Phytase expressed as phytase units (FTU) per kg of diet.

Table 4.3: Composition of 3 sources of hybrid rye, barley, wheat, corn, and sorghum, as-fed basis

Item	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	Sorghum
DM, %	87.56	88.15	87.19	88.17	87.85	88.10	89.63
GE, kcal/kg	3,763	3,797	3,772	3,829	3,867	3,874	3,936
CP, %	8.65	9.08	8.90	10.54	11.35	7.20	10.19
Ash, %	1.48	1.55	1.46	1.34	1.76	1.21	1.44
Macro minerals[1], %							
Ca	0.03	0.03	0.03	0.03	0.03	0.01	0.01
K	0.44	0.42	0.40	0.31	0.43	0.36	0.29
Mg	0.10	0.10	0.11	0.09	0.13	0.08	0.11
P	0.26	0.32	0.29	0.27	0.36	0.23	0.28
S	0.11	0.12	0.11	0.14	0.14	0.09	0.11
Micro minerals[1], mg/kg							
Cu	0.48	0.42	0.95	0.94	1.12	<0.10	3.14
Fe	28.20	25.00	31.40	25.30	37.80	17.30	32.00
Mn	16.90	22.00	13.90	10.90	37.70	3.64	12.10
Zn	23.30	23.20	27.00	24.10	27.80	18.20	17.20
Phytate, %	0.71	0.88	0.78	0.64	0.99	0.66	0.73
Phytate-bound P[2], %	0.20	0.25	0.22	0.18	0.28	0.19	0.21
Non-phytate P[3], %	0.06	0.07	0.07	0.09	0.08	0.04	0.07
Phytase, FTU[4]	3,000	3,200	2,300	490	580	<70	80

Table 4.3 (Cont.)

[1]Cl, Na, Se and I were analyzed but were not detected. The detectable limit was 0.10% for Cl, 0.01% for Na, 20 mg per kg for Se, and 100 mg per kg for I.

[2]Phytate-bound P was calculated as 28.2% of phytate (Sauvant et al., 2004).

[3]Non-phytate P was calculated as total P (%) minus phytate-bound P (%).

[4]Intrinsic phytase expressed as phytase units (FTU) per kg of grain.

Table 4.4: Daily feed and P intake, apparent total tract digestibility (ATTD), and standardized total tract digestibility (STTD) of P in experimental diets

Treatment	Feed intake, g/d	Fecal output, g/d	P intake, g/d	P in feces, %	P output, g/d	ATTD of P, %	STTD of P[1], %
Without phytase							
Rye 1	640	77.5	1.41	1.09[cde]	0.84[bc]	40.9[efg]	48.7[de]
Rye 2	535	63.8	1.34	1.28[bc]	0.78[bcd]	41.9[defg]	48.8[de]
Rye 3	579	70.0	1.57	1.16[bcd]	0.79[bcd]	49.1[bcdef]	55.5[bcd]
Barley	605	50.0	1.39	1.79[a]	0.87[abc]	37.0[fg]	44.6[de]
Wheat	446	52.5	1.38	1.91[a]	0.99[ab]	31.0[g]	36.6[ef]
Corn	572	51.4	1.15	1.85[a]	0.94[ab]	16.3[h]	24.9[fg]
Sorghum	519	58.8	1.19	1.97[a]	1.13[a]	9.5[h]	17.0[g]
With phytase, 1,000 FTU[2]							
Rye 1	546	61.3	1.20	0.90[e]	0.56[def]	54.1[abcd]	61.9[abc]
Rye 2	520	60.0	1.30	0.96[de]	0.57[def]	56.1[abc]	63.0[abc]
Rye 3	661	75.0	1.79	0.86[e]	0.63[cdef]	64.4[a]	70.8[a]
Barley	554	40.0	1.28	1.21[bcd]	0.48[f]	60.2[ab]	67.8[ab]
Wheat	501	53.8	1.56	1.38[b]	0.74[bcde]	51.9[abcde]	57.6[bcd]
Corn	563	47.5	1.12	1.07[cde]	0.51[ef]	53.8[abcde]	62.5[abc]
Sorghum	505	55.0	1.16	1.10[cde]	0.62[cdef]	46.1[cdef]	53.6[cd]

Table 4.4 (Cont.)

	Feed intake, g/d	Fecal output, g/d	P intake, g/d	P in feces, %	P output, g/d	ATTD of P, %	STTD of P[1], %
SEM	37.5	3.64	0.093	0.061	0.060	3.58	3.58
P – value							
Grain	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Phytase	0.739	0.088	0.975	<0.001	<0.001	<0.001	<0.001
Interaction	0.251	0.402	0.217	<0.001	0.010	<0.001	<0.001

[a-h] Means in a column without a common superscript differ ($P < 0.05$).

[1]STTD of P was calculated by correcting ATTD of P for basal endogenous losses of P. A basal endogenous loss of P of 190 mg per kg DM intake was assumed for all pigs (NRC, 2012).

[2]Phytase expressed as phytase units (FTU) per kg of diet.

Table 4.5: Daily Ca intake and apparent total tract digestibility (ATTD) of Ca in experimental diets

Treatment	Ca intake, g/d	Ca in feces, %	Ca output, g/d	ATTD of Ca, %
Without phytase				
Rye 1	2.50	0.89^{cde}	0.68^{abc}	72.8^{cde}
Rye 2	2.15	1.01^{bc}	0.56^{bcd}	70.7^{def}
Rye 3	2.32	0.81^{cde}	0.56^{bcd}	76.1^{abcd}
Barley	2.36	1.35^{ab}	0.69^{abc}	71.8^{cdef}
Wheat	1.78	0.94^{cd}	0.49^{cd}	74.4^{def}
Corn	2.35	1.69^{a}	0.86^{a}	62.9^{ef}
Sorghum	2.17	1.41^{a}	0.75^{ab}	64.9^{f}
With phytase, 1,000 FTU[1]				
Rye 1	2.13	0.86^{cde}	0.52^{bcd}	75.3^{abcd}
Rye 2	2.07	0.64^{de}	0.39^{d}	81.5^{abc}
Rye 3	2.65	0.56^{e}	0.41^{d}	84.6^{a}
Barley	2.17	0.81^{cde}	0.32^{d}	84.8^{a}
Wheat	2.02	0.64^{de}	0.33^{d}	83.2^{ab}
Corn	2.30	1.06^{bc}	0.45^{cd}	77.8^{abcd}
Sorghum	2.12	0.96^{cd}	0.54^{bcd}	74.5^{bcd}
SEM	0.150	0.073	0.066	2.30
P – value				
Grain	0.006	<0.001	<0.001	<0.001
Phytase	0.784	<0.001	<0.001	<0.001
Interaction	0.251	<0.001	0.032	0.022

[a-f] Means in a column without a common superscript differ ($P < 0.05$).

[1]Phytase expressed as phytase units (FTU) per kg of diet.

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CHAPTER 5: METABOLIZABLE ENERGY IN HYBRID RYE IS NOT DIFFERENT FROM BARLEY AND SORGHUM, BUT MICROBIAL FERMENTATION OF FIBER CONTRIBUTES A GREATER PROPORTION OF ENERGY TO PIGS FED HYBRID RYE COMPARED WITH PIGS FED BARLEY, WHEAT, CORN, OR SORGHUM

ABSTRACT

An experiment was conducted to determine the apparent ileal digestibility (AID) and the apparent total tract digestibility (ATTD) of energy, starch, and total dietary fiber (TDF) in 2 varieties of hybrid rye and compare these values with values obtained for barley, wheat, corn, and sorghum. It was hypothesized that there are no differences in AID and ATTD of energy and nutrients among hybrid rye, barley, wheat, and sorghum. Twenty-four ileal cannulated barrows (initial BW = 28.1 ± 3.0 kg) were randomly allotted to a 2-period experimental design with 6 diets and 4 replicate pigs in each period for a total of 8 replicate pigs per diet. Diets consisted of 97% of each grain, and each pig received a different diet in each period. The initial 5 d of each period were considered adaptation, whereas urine and fecal materials were collected the following 4 d, and ileal digesta were collected on d 12 and 13. Values for AID and ATTD of energy, starch, and TDF were calculated at the conclusion of the experiment. Results indicated that the ME on a DM basis was greatest ($P < 0.05$) in corn and wheat (3,732 and 3,641 kcal/kg DM), and least ($P < 0.05$) in barley (3,342 kcal/kg DM), whereas the 2 hybrid ryes contained 3,499 and 3,459 kcal/kg DM, respectively. These values were not different from the ME in barley and sorghum. In all grains, the AID of starch was greater than 90%, and the ATTD of starch was nearly 100%. Barley contained more TDF than the other cereal grains, and the 2 hybrid ryes had concentrations of soluble dietary fiber that were close to the concentration in

barley. The AID of TDF was less than 35% for all cereal grains, but the ATTD of TDF was greater ($P < 0.05$) in the 2 hybrid ryes than in the other ingredients. In conclusion, rye results in reduced pre-cecal absorption of energy compared with wheat, corn, and sorghum, but because hindgut fermentation of fiber is greater in rye than in other cereal grains, the ME in hybrid rye is not different from the ME in barley and sorghum. However, the ME in hybrid rye is less than in corn and wheat.

Keywords: cereal grains, energy digestibility, fiber digestibility, hybrid rye, pigs, starch digestibility

INTRODUCTION

The production of hybrid rye in North America is currently increasing, particularly in Canada and in the upper Midwestern U.S. Due to greater yields, better overwintering ability, and improved drought tolerance, hybrid rye can be an attractive alternative to growing barley, wheat, or sorghum, especially on poor soil (Geiger and Meidaner, 2009). Hybrid rye can be used in the human food industry for baking and distilling, in biogas production, or as a livestock feed. However, there are currently no published values for ME in hybrid rye when fed to pigs, and it has been demonstrated that the digestible nutrient composition of new hybrids of rye are different from older cultivars of rye (Strang et al., 2016; McGhee and Stein, 2018). The fiber composition of hybrid rye is different from barley, wheat, corn, and sorghum (Rodehutscord et al., 2016; McGhee and Stein, 2018), and the extent of fermentation of fiber from hybrid rye in the small and large intestine of growing pigs is not well documented. Rye has greater concentrations of arabinoxylans and fructooligosaccharides than barley, wheat, corn, and sorghum, and a greater concentration of mixed-linked β-glucans than wheat, corn, and sorghum

(Rodehutscord et al., 2016; McGhee and Stein, 2018). It is hypothesized that the fiber fraction is fermented differently in rye compared with other cereal grains, which may provide health benefits to animals (Bach Knudsen et al., 2005; 2016; 2017). However, at this time, digestion and fermentation of energy and fiber in hybrid rye fed to pigs have not been reported. Therefore, it was the objective of this experiment to determine the apparent ileal digestibility (**AID**) and the apparent total tract digestibility (**ATTD**) of starch, energy, and dietary fiber in hybrid rye and compare these values with values obtained for barley, wheat, corn, and sorghum. It was hypothesized that the digestion and fermentation of carbohydrates and other nutrients in hybrid rye will result in DE and ME in hybrid rye that are not different from values obtained for barley, wheat, and sorghum. Due to the greater concentration of starch expected in corn, it was hypothesized that corn will have greater DE and ME than hybrid rye.

MATERIALS AND METHODS

The experiment was conducted at the Swine Research Center at the University of Illinois following a protocol that was approved by the Institutional Animal Care and Use Committee at the University of Illinois.

Animals, Housing, and Experimental Design

Twenty-four growing barrows (initial BW = 28.1 ± 3.0 kg) that were the offspring of PIC Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN) were prepared with a T-cannula in the distal ileum as previously described (Stein et al., 1998). Pigs were housed in individual metabolism crates that were equipped with a self-feeder, a nipple waterer, and slatted floors to allow for the total, but separate, collection of urine and fecal materials. Throughout the experiment, pigs had *ad libitum* access to water. Following a 7-d recovery period from surgery, animals were allotted to a 2-period experimental design with 6 diets. There were 4 replicate pigs per diet in each period for a total of 8 replicate pigs per diet. All pigs received a different diet in the second period than they received in the first period.

Two sources of hybrid rye (KWS Lochow GmbH, Bergen, Germany), and one source of hulled barley, wheat, corn, and sorghum were ground through a hammer mill (model WA-8-H; Schutte Buffalo LLC, Buffalo, NY) with a 1.59 mm screen, and each source of grain was used in one diet (Table 1). One of the hybrids of rye was grown in Canada in 2017, but all other grains used in the experiment were grown in the U.S. in 2017. Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for 25 to 50 kg growing pigs (NRC, 2012). Diets also contained 0.5% titanium dioxide, which was an indigestible marker.

Feeding and Sample Collection

Pigs were limit fed at 3.2 times the estimated ME requirement for maintenance (i.e., 197 kcal ME per kg $BW^{0.60}$; NRC, 2012), which was provided each day in 2 equal meals at 0800 and 1700 h. The ME of each diet was estimated based on ME values for each ingredient as reported by NRC (2012). Feed consumption was recorded daily, and diets were fed for 13 d. The initial 5 d were considered the adaptation period to the diet, whereas urine and fecal materials were collected during the following 4 d according to standard procedures using the marker-to-marker approach (Adeola, 2001). Ileal digesta samples were collected on d 12 and 13 as previously explained (Stein et al., 1998). Urine was collected in urine buckets over a preservative of 50 mL of 6*N* HCl. Fecal samples, 20% of the collected urine, and ileal digesta were stored at -20 ^{o}C immediately after collection.

Chemical and Physical Analyses

At the conclusion of the experiment, urine and ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized. Urine samples were filtered through a Whatman grade 4 filter paper prior to analysis, and ileal digesta samples were finely ground using a coffee grinder. Fecal samples were dried in a forced air oven and ground using a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ).

All diets, ingredients, fecal samples, and ileal digesta samples were analyzed for DM (method 930.15; AOAC Int., 2007). Diet and ingredient samples were analyzed for ash (method 942.05; AOAC Int., 2007) and for CP (method 990.03; AOAC Int., 2007) using a Leco Nitrogen Determinator (model FP628, Leco Corp., St. Joseph, MI). Ingredient samples were analyzed for ADF and NDF using Ankom Technology methods 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY). After ADF analysis, ADL was determined using Ankom Technology method 9 (Ankom Daisy II Incubator, Ankom Technology, Macedon, NY).

Diet, ingredient, ileal, and fecal samples were analyzed for insoluble dietary fiber (**IDF**) and soluble dietary fiber (**SDF**) on an Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon, NY) using method 991.43 (AOAC Int., 2007). Total dietary fiber (**TDF**) was calculated as the sum of IDF and SDF. The GE in diets, ingredients, fecal samples, urine samples, and ileal digesta were measured using an isoperibol bomb calorimeter (model 6400, Parr Instruments, Moline, IL) with benzoic acid used as the standard for calibration. Urine samples were prepared before GE analysis as previously described (Kim et al., 2009). Ingredient samples were analyzed for ether extract by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY). Total acid-hydrolyzed ether extract was determined using the same procedure, but samples were hydrolyzed prior to extraction using 3*N*

HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY). Diets and ingredients were also analyzed for AA on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for post-column derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* HCl for 24 h at 110 °C (method 982.30 E[a]; AOAC Int., 2007). Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E[b]; AOAC Int., 2007). Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C (method 982.30 E[c]; AOAC Int., 2007). The titanium dioxide concentration was determined in diets and ileal digesta samples following the procedure by Myers et al. (2004). The concentration of total starch in diets, ileal digesta, and fecal samples was analyzed by the glucoamylase procedure (method 979.10; AOAC Int., 2007), which yields the enzymatically hydrolyzed starch in the samples.

Mycotoxin analysis on all cereal grains was performed at Trilogy Analytical Laboratories (Washington, MO) using liquid chromatography-tandem mass spectroscopy. The minimum detectable concentrations of mycotoxins were as follows: aflatoxin B1 (1 µg/kg), aflatoxin B2 (1 µg/kg), aflatoxin G1 (1 µg/kg), aflatoxin G2 (1 µg/kg), deoxynivalenol (0.1 mg/kg), fumonisin B1 (1 µg/kg), fumonisin B2 (1 µg/kg), fumonisin B3 (1 µg/kg), zearalenone (12.5 µg/kg), ochratoxin A (1 µg/kg), 3-acetyl deoxynivalenol (0.1 mg/kg), 15-acetyl deoxynivalenol (0.1 mg/kg), fusarenon-X (0.1 mg/kg), nivalenol (0.1 mg/kg), neosolaniol (0.1 mg/kg), diacetoxyscirpenol (0.1 mg/kg), HT-2 toxin (5 µg/kg), T-2 toxin (µg/kg), and citrinin (50 µg/kg). The concentration of ergot alkaloids was determined by refractive index HPLC using Phenomenex Strata-X-CW (Phenomenex, Inc., Torrance, CA) weak cation exchange and reversed phase column. The minimum detectable concentration of ergot alkaloids was 10 µg/kg.

Particle size of ingredients was analyzed with a Ro-Tap Sieve Shaker (W.S. Tyler, Mentor, OH) with 13 sieves of sieve opening sizes 53 to 3,360 µm (procedure S319.4, ANSI/ASAE, 2008).

Calculations and Statistical Analyses

The DE and ME in diets were calculated by subtracting the GE in the feces and the GE in the feces and urine, respectively, from the GE in the diet (NRC, 2012). The DE and ME in the ingredients were calculated by dividing the DE and ME in the diets by the ingredient inclusion rate, which was approximately 97% in all diets. The NE in each ingredient was calculated using the following prediction equation based on the DE and nutrient composition of each ingredient, where EE is ether extract (NRC, 2012):

$$\mathrm{NE} = (0.700 \times \mathrm{DE}) + (1.61 \times \mathrm{EE}) + (0.48 \times \mathrm{starch}) - (0.91 \times \mathrm{CP}) - (0.87 \times \mathrm{ADF})$$

The ATTD of energy, starch, and fiber components (IDF, SDF, TDF) was calculated for each diet using the following equation (Adeola, 2001):

$$\mathrm{ATTD}_{\mathrm{nutrient}}, \% = \left(\frac{\mathrm{Nutrient}_{\mathrm{intake}} - \mathrm{Nutrient}_{\mathrm{feces}}}{\mathrm{Nutrient}_{\mathrm{intake}}}\right) \times 100$$

The AID of DM, GE, starch, and fiber components was calculated for each diet using the following equation (Stein et al., 2007):

$$\mathrm{AID}_{\mathrm{nutrient}}, \% = 100 - \left[\left(\frac{\mathrm{Nutrient}_{\mathrm{digesta}}}{\mathrm{Nutrient}_{\mathrm{feed}}}\right) \times \left(\frac{\mathrm{Ti}_{\mathrm{feed}}}{\mathrm{Ti}_{\mathrm{digesta}}}\right)\right] \times 100$$

Hindgut disappearance (**HGD**) of DM, GE, starch, and fiber components was calculated using the following equation (Högberg and Lindberg, 2004):

$$\mathrm{HGD}_{\mathrm{nutrient}}, \% = \mathrm{ATTD}_{\mathrm{nutrient}}, \% - \mathrm{AID}_{\mathrm{nutrient}}, \%$$

Data were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC). The pig was the experimental unit for all analyses. An outlier was defined as an observation with a studentized residual of greater than 3 or less than -3 and was subsequently removed from further statistical analysis. PROC UNIVARIATE and PROC GPLOT were used to check model assumptions. The statistical model in PROC MIXED included source of grain as the fixed effect and pig and period as random effects. The model was fitted with the restricted maximum likelihood (REML) method and the degrees of freedom were estimated using the Kenward-Rogers approach. Least squares means were estimated and separated using the PDIFF statement with Tukey-Kramer adjustment in PROC MIXED. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

RESULTS

All pigs recovered from surgery without complications and consumed their diets throughout the experiment without apparent problems. Nutrient compositions of diets were in agreement with formulated values (Table 1). Gross energy among ingredients ranged from 3,824 kcal/kg in corn to 3,974 kcal/kg in barley (Table 2). Sorghum contained the most starch (62.30%), followed by corn, wheat, the 2 sources of hybrid rye, and barley. One source of rye contained 56.56% starch, and the other source contained 54.90%. Barley contained 19.0% TDF, which was the most among all ingredients, and it consisted of 16.4% IDF and 2.6% SDF. The 2 sources of hybrid rye contained slightly less IDF and SDF than barley, but wheat, corn, and sorghum contained less TDF than the barley and rye. The second source of hybrid rye, as well as barley and corn contained 0.9, 0.2, and 0.1 mg/kg deoxynivalenol, respectively, and corn also contained 0.3 µg/kg of fumonisin B1 and 28.9 µg/kg zearalenone (Table 3). The 2 hybrid ryes contained 0.22 and 0.08 mg/kg ergot alkaloids, whereas the other ingredients had concentrations of ergot alkaloids below the detectable limit of 10 µg/kg.

The average concentration of GE consumed daily by the pigs was greatest ($P < 0.05$) for barley (5,773 kcal/d) and least for sorghum (4,060 kcal/d), and the concentration of GE in feces was greatest ($P < 0.05$) for barley (1,111 kcal/d) and least for corn (468 kcal/d; Table 4). The concentration of GE in urine was not different among cereal grains and ranged from 130 kcal/d to 185 kcal/d. The AID of GE was greater ($P < 0.05$) in wheat, corn, and sorghum than in hybrid rye and barley. The ATTD of GE was greatest ($P < 0.05$) in corn, followed by wheat, sorghum, hybrid rye, and barley. There were no differences in the ATTD of GE between corn and wheat, nor were there differences between the 2 hybrids of rye and sorghum, however, the ATTD of GE was less ($P < 0.05$) in barley than in all other cereal grains. The HGD of GE was greatest ($P < 0.05$) in hybrid rye, followed by barley, wheat, corn, and sorghum.

On a DM basis, concentrations of DE and ME were greatest ($P < 0.05$) in corn and wheat. The DE in sorghum was less ($P < 0.05$) than in corn, but not different from the DE in wheat and one source of hybrid rye. The ME in sorghum was also less ($P < 0.01$) than in corn, but not different from wheat or the 2 hybrid ryes. The DE in barley was less ($P < 0.05$) than in all other ingredients, and the ME in barley was less ($P < 0.05$) than in all cereal grains except in one source of hybrid rye. The NE was greater ($P < 0.05$) in corn than in all other grains, and wheat and sorghum had NE values that were not different from each other but greater than in barley and both sources of hybrid rye. The NE in barley was less ($P < 0.05$) than in all other ingredients.

The AID of DM was greater ($P < 0.05$) in wheat, corn, and sorghum than in the 2 hybrids of rye and barley (Table 5). The AID of starch was greater than 90% in all cereal grains, with wheat having the greatest ($P < 0.05$) AID of starch and one source of hybrid rye having the least ($P < 0.05$). The AID of TDF was less than 30% in all grains, but it was greatest ($P < 0.05$) in sorghum and least ($P < 0.05$) in one source of hybrid rye. Similarly, the AID of IDF was greatest

($P < 0.05$) in sorghum and least in one source of hybrid rye. The calculated values for AID of SDF were negative for all ingredients except in one source of hybrid rye and ranged from -306.1% to 0.9%. Because there was no analyzed SDF in corn, the AID and ATTD of SDF could not be calculated for that ingredient.

The ATTD of DM was greatest ($P < 0.05$) in corn and wheat, followed by sorghum, hybrid rye, and barley. The ATTD of starch was nearly 100% for all grains, although there was a statistical difference ($P < 0.05$) between corn and barley. The ATTD of TDF was greater ($P < 0.05$) in the 2 hybrids of rye than in the other grains, with digestibility values of 68.3% and 70.8%. The ATTD of TDF in the other grains ranged from 56.1% in barley to 58.2% in wheat. The ATTD of IDF was also greater ($P < 0.05$) in the hybrids of rye than in the other ingredients. Among rye, barley, wheat, and sorghum, the ATTD of SDF was greatest ($P < 0.05$) in one source of hybrid rye and barley, and least ($P < 0.05$) in wheat and sorghum.

The HGD of DM was greater ($P < 0.05$) in one source of hybrid rye than in all other cereal grains. One source of hybrid rye, which had reduced ($P < 0.05$) AID of starch, had greater ($P < 0.05$) HGD of starch than wheat; however, there were no differences among the other grains. One source of hybrid rye also had the greatest ($P < 0.05$) HGD of TDF and IDF, but there were no differences in HGD of TDF among the second source of hybrid rye, barley, wheat, and corn. The HGD of SDF could not be calculated for corn, but the one source of hybrid rye and wheat had greater ($P < 0.05$) HGD of SDF than the other cereal grains. The HGD of SDF in the one source of hybrid rye, barley, and wheat were greater than 100% due to the strongly negative AID of SDF and positive ATTD of SDF.

DISCUSSION

Concentrations of starch and GE in each of the cereal grains were within expected values, (NRC, 2012; Cervantes-Pahm et al., 2013; Evonik Industries, 2016; Rodehutscord et al., 2016; Stein et al., 2016; Rostagno et al., 2017) although some variation was observed. The concentration of CP in both hybrid ryes was lower than previously reported for older cultivars of rye, but very close to published values for hybrid rye (NRC, 2012; Lærke et al., 2015; Strang et al., 2016; McGhee and Stein, 2018). The concentration of TDF was also in close agreement with published data, although most of the cereal grains used in the present experiment differed slightly from some previous feed tables (NRC, 2012; Cervantes-Pahm et al., 2013; Lærke et al., 2015; Strang et al., 2016; McGhee and Stein, 2018). The TDF in sorghum is reported to be 4.93% and starch is reported to be 70.05% (NRC, 2012); however, in the present experiment, and in other publications (Cervantes-Pahm et al., 2013; Evonik Industries, 2016), the concentration of TDF is closer to 8 to 9% in sorghum, whereas starch is 62 to 67%. Likewise, in modern hybrids of rye, it is possible the concentrations of TDF and starch differ from older cultivars, but there are limited data available for TDF in rye (Bach Knudsen, 1997; Salmenkallio-Marttila and Hovinen, 2005; NRC, 2012; Cervantes-Pahm, 2013; Strang et al., 2016; McGhee and Stein, 2018).

The AID of starch in all cereals was in agreement with published data (Cervantes-Pahm et al., 2013; Lærke et al., 2015; Rojas and Stein, 2015). The AID of starch in rye and wheat is sometimes reported to be nearly 100% in pigs fed bread based diets, but baking increases starch gelatinization, and therefore also increases the speed and extent starch is digested compared with raw cereal based diets (Cummings and Englyst, 1995; Bach Knudsen et al., 2005; Le Gall et al., 2010). The observation that the AID of starch was greater than 90% in all grains in the present experiment is likely due to the small particle size of the ingredients used, as reducing the particle size of cereal grains increases the AID of starch (Rojas and Stein, 2015). The structure of starch in rye differs from wheat, which may result in slower hydrolysis and reduced AID of starch (Juntunen et al., 2003; Bach Knudsen et al., 2005; Le Gall et al., 2010). Wheat contains more type B granules of starch that are resistant to pancreatic enzymes, but the granules of starch in rye are generally larger and more tightly packed than in wheat, which may reduce the efficacy of amylase digestion in the granules (Juntunen et al., 2003; Buksa, 2018). Although conflicting results have been reported, the reduced AID of starch observed in rye compared with wheat may also be due to increased intestinal viscosity (Bach Knudsen et al., 2005; Le Gall et al., 2010; Laerke et al., 2015). In rye, high extract viscosity is a primary breeding goal because it improves bread dough quality, but it may have negative consequences in the gastrointestinal tract of pigs (Jürgens et al., 2012). Increased viscosity increases water-binding capacity and reduces digesta passage rate, endogenous enzyme efficacy, and glucose absorption, although the effects are more pronounced in poultry than in pigs (Antoniou et al., 1981; Lærke et al., 2008; Le Gall et al., 2009; Jürgens et al., 2012; Zuber et al., 2016). If intestinal viscosity is not the main reason for reduced digestion of starch in rye, it may be due to arabinoxylans resisting degradation in the small intestine, consequently impairing digestibility of starch by blocking enzyme accessibility to starch or other nutrients (Le Gall et al., 2009; 2010; Kasprzak et al., 2012).

Soluble dietary fiber is primarily fermented in the cecum (Jaworski and Stein, 2017), and the AID of SDF, therefore, was expected to be low. The reason values for AID of SDF were mostly negative is that some of the IDF in the grains may have become solubilized in the stomach and analyzed as SDF in the ileal digesta (Abelilla and Stein, 2019a). It is also likely that endogenous losses from the pig, including mucin, are analyzed as SDF in the ileal digesta, causing the ileal output of SDF to appear high in comparison with the dietary intake of SDF (Montoya et al., 2015). Because the intake of SDF was low for all grains, inclusion of mucin and microbial matter in the analyzed SDF in the ileal digesta may result in negative values being calculated for the AID of SDF, which has also been previously demonstrated (Cervantes-Pahm et al., 2014; Montoya et al., 2015). The grains that had the greatest concentrations of SDF had the least negative values for AID of SDF, which further indicates that the reason for negative AID values was solubilization of IDF and/or endogenous secretions that were analyzed as SDF.

The ATTD of SDF may be between 90 and 98% in corn distiller's dried grains with solubles and wheat (Urriola et al., 2010; Navarro et al., 2018), but the values obtained for cereal grains in the present experiment were much lower. Due to the very small quantities of SDF in most cereal grains, any variation or error in the analysis of the grain will greatly impact the calculation of digestibility. The arabinoxylans in rye are more soluble and fermentable than the arabinoxylans in other cereal grains due to their structure (Karppinen, 2003; Le Gall et al., 2009; 2010), and rye and barley contain considerable amounts of fermentable mixed-linked β-glucans (Bach Knudsen and Hansen, 1991; Bach Knudsen, 1997; Rodehutscord et al., 2016). Thus, the fiber components themselves were likely the reason for the increased ATTD of SDF observed in hybrid rye and barley compared with wheat and sorghum. It is unlikely the small concentrations of SDF in cereal grains provide substantial energy to the pig (Jaworski and Stein, 2017), but although highly fermentable, elevated concentrations of SDF increase viscosity and potentially reduces nutrient digestibility (Bach Knudsen, 1997; Le Gall et al., 2010; Jürgens et al., 2012;).

Disappearance of fiber prior to the cecum may be due to the partial degradation of arabinoxylans and subsequent absorption of arabinose and xylose, and these monosaccharides have limited energetic value when absorbed by the pig because they will largely be excreted in the urine (Schutte et al., 1991; Yule and Fuller, 1992; Huntley and Patience, 2018a; 2018b; Abelilla and Stein, 2019b). Therefore, even though the AID of IDF and TDF was greater in sorghum and one source of hybrid rye than in other grains, pre-cecal degradation of fiber does not necessarily result in increased energy synthesis (Abelilla and Stein, 2019b).

It is not clear why there was a substantial difference in AID of DM, SDF, IDF, and TDF between the 2 hybrids of rye, but it may be due to differences in the composition of the fiber in the grain. The α-amylase activity, soluble fiber content, structure of arabinoxylans, formation of cross-linkages between fiber and other macromolecules, and extract viscosity are all influenced by growing and harvesting conditions, as well as the genotype of the plant (Drews and Seibel, 1976; Bengtsson et al., 1992; Ragaee et al., 2001; Hansen et al., 2003; Jürgens et al., 2012; Laidig et al., 2017). Additionally, the fiber structure and fermentability depends on the location in the grain, as fiber from the endosperm is much more fermentable than fiber from the pericarp or testa (Glitsø et al., 1999). If the chemical composition of fiber and/or gross structure of the grain varied greatly between the 2 genotypes of hybrid rye used in the present experiment, these factors may explain the differences observed for nutrient digestion and fiber fermentation between the 2 hybrids of rye (Bach Knudsen et al., 2005; Le Gall et al., 2009).

Although microbial fermentation occurs throughout the gastrointestinal tract, most microbial fermentation of IDF and subsequent short-chain fatty acid synthesis occurs in the colon, so ATTD, rather than AID, of IDF and TDF is a more meaningful estimation of fiber fermentation (Jensen and Jørgensen, 1994; Jaworski and Stein, 2017). The greater ATTD of IDF and TDF in hybrid rye than in the other grains indicates that more microbial fermentation of fiber occurred in pigs fed rye. The AID of DM in one source of hybrid rye was less than in wheat, corn, and sorghum, hence, more substrate was available to microbes in the large intestine. The fiber components in rye are more fermentable than in other grains (Le Gall et al., 2010; Cervantes-Pahm et al., 2013), which in combination with greater amounts of unabsorbed material entering the hindgut explains why the HGD of DM, starch, and dietary fiber was greater in one hybrid of rye than in the other cereal grains. Rye fiber primarily consists of arabinoxylans, fructooligosaccharides, mixed-linked β-glucans, and cellulose, and fermentation of rye fiber results in increased synthesis of butyrate, a preferred source of energy for colonocytes and a promoter of gut health (Glitsø et al., 1998; Bach Knudsen et al., 2005; Le Gall et al., 2009). In the present experiment, not only was a greater proportion of fiber in hybrid rye fermented (as evidence by the greater ATTD of TDF than in all other grains), but hybrid rye contained more TDF than wheat, sorghum, and corn, so the total amount of fiber fermented was greater as well. In contrast, barley had the greatest amount of TDF among the cereal grains but had lower ATTD of DM and TDF than hybrid rye, so when pigs are fed barley, more fiber will be excreted in the feces than if pigs are fed rye, and this may pose challenges for manure handling and storage (Petersen, 2010; Van Weelden et al., 2016).

On a DM basis, the values obtained for the DE, ME, and NE in hybrid rye were within 100 kcal/kg of most previously published values for rye, and the same was true for barley (NRC, 2012; Evonik Industries, 2016; Rostagno et al., 2017). The reason the AID of GE, ATTD of GE, and ME are greater in corn and wheat than in rye and barley is likely that corn and wheat contain more starch, and starch provides more energy to the animal than fiber. Microbial fermentation of fiber results in the synthesis and absorption of short-chain fatty acids; however, endogenous enzymatic digestion of starch is more efficient and yields more energy than fiber fermentation (Nelson and Cox, 2004). Fiber may also form cross-linkages with cell wall proteins or interfere with bile acid formation, thereby reducing the digestibility of AA and lipid, and consequently GE as well (Bach Knudsen et al., 2005; Le Gall et al., 2009; Urriola et al., 2013). Barley and rye contain more TDF than the other cereal grains, but only limited fermentation of fiber occurs in the small intestine (Jensen and Jørgensen, 1994; Nitrayová et al., 2009; Lærke et al., 2015). Therefore, when barley or rye is fed to pigs, more fiber, as well as more endogenous material (Cunningham et al., 1962; Souffrant, 2001; Cervantes-Pahm et al., 2014; Montoya, 2015; Agyekum and Nyachoti, 2017), will exit the small intestine, thus increasing the analyzed GE in ileal digesta and reducing the AID of GE. Although the AID of GE was markedly reduced in barley and rye compared with wheat, corn, and sorghum, the HGD of GE was greater in one of the rye hybrids than in barley, wheat, corn, and sorghum, and this resulted in no difference in the ATTD of GE among that specific hybrid of rye and wheat and sorghum. The greater HGD of GE that occurred in hybrid rye as a result of microbial fiber fermentation partially compensated for the reduced pre-cecal energy digestibility, and thus, the ME in hybrid rye was not different from sorghum or barley.

In conclusion, the ME calculated in the present experiment for hybrid rye did not differ from published values for rye. Rye results in reduced pre-cecal absorption of energy compared with wheat, corn, and sorghum, but hindgut fermentation of fiber is greater in rye than in other cereal grains. The greater HGD of DM, starch, IDF, TDF, and GE in rye than in other grains demonstrates that a greater proportion of the energy from rye is obtained from hindgut fermentation when pigs are fed hybrid rye compared with other grains, so overall, feeding hybrid rye will provide ME that is not different from that provided by barley or sorghum, but less than by wheat and corn. Hybrid rye also appears to provide less NE than wheat, corn, and sorghum, but more NE than barley, so diets should be formulated accordingly to account for the different amounts of energy contributed by different cereal grains.

TABLES

Table 5.1: Composition of experimental diets, as-fed basis

Item	Rye 1	Rye 2	Barley	Wheat	Corn	Sorghum
Ingredient, %						
Cereal grain	96.85	96.85	96.95	97.10	96.70	96.85
Ground limestone	1.05	1.05	0.95	1.20	0.80	1.05
Dicalcium phosphate	1.05	1.05	1.05	0.65	1.45	1.05
Titanium dioxide	0.50	0.50	0.50	0.50	0.50	0.50
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[1]	0.15	0.15	0.15	0.15	0.15	0.15
Analyzed composition						
DM, %	90.55	90.13	92.41	90.68	87.68	88.36
GE, kcal/kg	3,762	3,702	3,855	3,793	3,656	3,705
CP, %	10.25	8.84	10.14	10.28	7.19	9.48
Ash, %	4.47	4.59	5.19	4.28	4.15	4.00
Starch, %	50.20	51.71	50.79	54.29	56.08	60.12
Insoluble dietary fiber, %	12.26	15.37	16.45	10.27	8.50	8.33
Soluble dietary fiber, %	1.30	2.73	2.55	0.52	ND[2]	0.71
Total dietary fiber, %	13.56	18.10	19.00	10.79	8.50	9.04

[1]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[2]ND = not detected.

Table 5.2: Analyzed composition and particle size of 2 sources of hybrid rye, barley, wheat, corn, and sorghum, as-fed basis

Item	Rye 1	Rye 2	Barley	Wheat	Corn	Sorghum
DM, %	90.09	90.32	92.62	89.98	87.72	88.03
GE, kcal/kg	3,866	3,837	3,974	3,870	3,824	3,844
CP, %	10.81	9.25	10.56	10.06	7.62	9.44
Ash, %	1.42	1.70	2.55	1.67	1.35	1.19
Ether extract, %	1.24	1.19	1.79	1.71	3.61	2.80
AEE[1], %	1.28	1.21	2.16	1.87	3.11	2.83
Starch, %	56.56	54.90	51.74	57.07	57.98	62.30
ADF, %	2.58	3.49	5.78	2.79	2.31	3.40
NDF, %	17.38	17.94	19.75	10.74	8.80	9.10
ADL, %	0.81	1.05	1.05	0.74	0.34	0.64
Insoluble dietary fiber, %	13.52	15.48	16.44	10.56	10.27	7.87
Soluble dietary fiber, %	1.70	2.79	2.55	0.75	ND[2]	0.10
Total dietary fiber, %	15.22	18.27	18.99	11.31	10.27	7.97
Indispensable AA, %						
Arg	0.51	0.45	0.51	0.51	0.36	0.30
His	0.23	0.20	0.23	0.23	0.21	0.18
Ile	0.39	0.32	0.39	0.36	0.27	0.34
Leu	0.66	0.55	0.70	0.67	0.84	1.06
Lys	0.41	0.37	0.43	0.37	0.28	0.21
Met	0.17	0.16	0.16	0.16	0.14	0.13
Phe	0.49	0.38	0.51	0.44	0.36	0.42
Thr	0.34	0.31	0.33	0.30	0.27	0.26
Trp	0.09	0.10	0.10	0.11	0.06	0.07
Val	0.50	0.42	0.53	0.45	0.36	0.40
Total	3.79	3.26	3.89	3.60	3.15	3.37

Table 5.2 (Cont.)

Item	Rye 1	Rye 2	Barley	Wheat	Corn	Sorghum
Dispensable AA, %						
Ala	0.44	0.40	0.48	0.39	0.54	0.74
Asp	0.70	0.65	0.65	0.57	0.52	0.54
Cys	0.25	0.23	0.24	0.26	0.17	0.16
Glu	2.53	1.85	2.46	2.59	1.30	1.64
Gly	0.46	0.41	0.43	0.44	0.31	0.27
Pro	1.01	0.71	1.04	0.86	0.65	0.66
Ser	0.41	0.34	0.39	0.41	0.33	0.34
Tyr	0.21	0.19	0.26	0.26	0.22	0.24
Total	6.01	4.78	5.95	5.78	4.04	4.59
Total AA, %	9.99	8.23	10.03	9.56	7.39	8.13
Particle size, µm	309	313	310	222	274	431

[1]AEE = Acid-hydrolyzed ether extract.

[2]ND = not detected.

Table 5.3: Mycotoxin concentration in 2 sources of hybrid rye, barley, wheat, corn, and sorghum, as-fed basis[1]

Toxin	Rye 1	Rye 2	Barley	Wheat	Corn	Sorghum
Deoxynivalenol, mg/kg	ND[2]	0.9	0.2	ND	0.1	ND
Fumonisin B1, µg/kg	ND	ND	ND	ND	0.3	ND
Zearalenone, µg/kg	ND	ND	ND	ND	28.9	ND
Ergot alkaloids, µg/kg	215.5	75.4	ND	ND	ND	ND

[1]The concentrations of the following mycotoxins were below detectable limits in all cereal grains, unless specified in the table*:* aflatoxin B1 (1 µg/kg), aflatoxin B2 (1 µg/kg), aflatoxin G1 (1 µg/kg), aflatoxin G2 (1 µg/kg), deoxynivalenol (0.1 mg/kg), fumonisin B1 (1 µg/kg), fumonisin B2 (1 µg/kg), fumonisin B3 (1 µg/kg), zearalenone (12.5 µg/kg), ochratoxin A (1 µg/kg), 3-acetyl deoxynivalenol (0.1 mg/kg), 15-acetyl deoxynivalenol (0.1 mg/kg), fusarenon-X (0.1 mg/kg), nivalenol (0.1 mg/kg), neosolaniol (0.1 mg/kg), diacetoxyscirpenol (0.1 mg/kg), HT-2 toxin (5 µg/kg), T-2 toxin (µg/kg), citrinin (50 µg/kg), and ergot alkaloids (10 µg/kg).

[2]ND = not detected.

Table 5.4: Apparent ileal digestibility (AID), apparent total tract digestibility (ATTD), and hindgut disappearance (HGD) of GE and concentration of DE, ME, and NE in 2 sources of hybrid rye, and in barley, wheat, corn, and sorghum

Item	Rye 1	Rye 2	Barley	Wheat	Corn	Sorghum	SEM	*P*-value
GE intake, kcal/d	4,535[bc]	4,973[b]	5,773[a]	4,826[b]	4,460[bc]	4,060[c]	213.3	<0.001
GE in feces, kcal/d	668[bc]	773[b]	1,111[a]	626[bc]	468[d]	565[cd]	47.6	<0.001
GE in urine, kcal/d	185	146	155	161	130	151	17.8	0.339
AID of GE, %	58.1[b]	65.4[b]	65.6[b]	74.3[a]	76.5[a]	77.4[a]	2.02	<0.001
ATTD of GE, %	85.4[bc]	84.7[c]	80.7[d]	87.4[ab]	89.5[a]	86.0[bc]	0.64	<0.001
HGD of GE, %	27.0[a]	19.6[ab]	15.1[bc]	13.2[bc]	13.0[bc]	8.6[c]	2.02	<0.001
DE, kcal/kg	3,316[bc]	3,237[cd]	3,208[d]	3,416[a]	3,384[ab]	3,291[bcd]	24.5	<0.001
DE, kcal/kg DM	3,682[cd]	3,583[d]	3,464[e]	3,796[ab]	3,858[a]	3,738[bc]	27.4	<0.001
ME, kcal/kg	3,153[b]	3,124[b]	3,095[b]	3,276[a]	3,274[a]	3,145[b]	32.1	<0.001
ME, kcal/kg DM	3,499[c]	3,459[cd]	3,342[d]	3,641[ab]	3,732[a]	3,573[bc]	35.9	<0.001
NE[1], kcal/kg DM	2,756[c]	2,704[c]	2,563[d]	2,875[b]	2,976[a]	2,866[b]	20.6	<0.001

[a-e]Means in a row without a common superscript differ (*P* < 0.05).

[1]Net energy was calculated using individual observations for DE (kcal/kg DM), and analyzed concentrations of ether extract, starch, CP, and ADF in each ingredient with Eq. 1-8 from NRC (2012).

Table 5.5: Apparent ileal digestibility (AID), apparent total tract digestibility (ATTD), and hindgut disappearance (HGD) of DM and carbohydrates in 2 sources of hybrid rye and in barley, wheat, corn, and sorghum

Item	Rye 1	Rye 2	Barley	Wheat	Corn	Sorghum	SEM	*P*-value
AID, %								
DM	59.5^{c}	66.9^{b}	65.2^{bc}	75.0^{a}	76.4^{a}	75.4^{a}	1.70	<0.001
Starch	91.2^{b}	95.9^{ab}	94.4^{ab}	97.8^{a}	95.2^{ab}	95.8^{ab}	1.47	<0.001
Insoluble dietary fiber	17.2^{c}	35.8^{ab}	27.3^{bc}	27.7^{bc}	24.3^{bc}	43.7^{a}	3.67	<0.001
Soluble dietary fiber	-225.9^{b}	0.9^{a}	-21.2^{a}	-306.1^{c}	-	-40.8^{a}	13.40	<0.001
Total dietary fiber	-5.7^{d}	28.8^{ab}	20.9^{abc}	11.8^{c}	13.6^{bc}	33.6^{a}	4.43	<0.001
ATTD, %								
DM	87.6^{b}	86.8^{b}	82.5^{c}	88.7^{ab}	90.2^{a}	87.8^{b}	0.49	0.001
Starch	99.0^{ab}	99.1^{ab}	98.8^{b}	99.3^{ab}	99.5^{a}	99.2^{ab}	0.15	0.044
Insoluble dietary fiber	67.3^{a}	67.0^{a}	49.5^{c}	58.9^{b}	60.3^{b}	58.6^{b}	1.71	<0.001
Soluble dietary fiber	72.5^{b}	89.7^{a}	89.3^{a}	52.6^{c}	-	51.4^{c}	3.17	<0.001
Total dietary fiber	68.3^{a}	70.8^{a}	56.1^{b}	58.2^{b}	57.9^{b}	58.0^{b}	1.74	<0.001
HGD, %								
DM	27.9^{a}	20.4^{b}	17.2^{bc}	13.9^{bc}	13.8^{bc}	12.2^{c}	1.79	<0.001
Starch	7.9^{a}	3.3^{ab}	4.4^{ab}	1.5^{b}	4.2^{ab}	3.4^{ab}	1.47	0.028
Insoluble dietary fiber	49.8^{a}	31.1^{bc}	22.6^{bc}	31.2^{bc}	37.1^{ab}	14.6^{c}	4.86	<0.001
Soluble dietary fiber	298.0^{a}	92.0^{b}	107.5^{b}	358.3^{a}	-	98.1^{b}	18.0	<0.001
Total dietary fiber	73.3^{a}	42.1^{bc}	35.7^{bc}	46.6^{b}	45.5^{b}	25.5^{c}	5.98	<0.001

$^{a\text{-}c}$Means in a row without a common superscript differ ($P < 0.05$)

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CHAPTER 6: CONCLUSIONS

Results of Exp. 1 demonstrate that hybrid rye contains similar quantities of standardized ileal digestible AA as corn; therefore, hybrid rye may replace corn in diets for pigs without reducing the provision of digestible AA. The standardized ileal digestibility (**SID**) of CP and most AA was, however, greater in barley, wheat, and corn than in hybrid rye. It is possible that the reason for the reduced SID of AA in hybrid rye is that fiber in rye reduces the efficiency of endogenous peptidases in the small intestine. The reduced digestibility of AA in hybrid rye may have consequences for pigs as excess N entering the large intestine may increase the presence of proteolytic bacteria. Further research should be conducted to evaluate growth performance and gut health when hybrid rye is fed to pigs.

Results from Exp. 2 indicate that the standardized total tract digestibility (**STTD**) of P in hybrid rye, without or with microbial phytase, is greater than or equal to barley, wheat, corn, and sorghum. It is likely that the greater P digestibility observed in hybrid rye is due to the greater intrinsic phytase activity in the grain. When microbial phytase was added to diets, the STTD of P increased in all ingredients, although the magnitude of the response differed among grains. In hybrid rye, which had a greater intrinsic phytase activity, the increase in digestibility of P when microbial phytase was added to the diet was less pronounced than in corn, which had very little intrinsic phytase activity. Because hybrid rye contains more total P than corn, the provision of standardized total tract digestible P is greater from hybrid rye than from corn regardless of microbial phytase inclusion, and less inorganic P will be needed if hybrid rye replaces corn in a swine diet.

In Exp. 3, it was observed that the ME in hybrid rye was less than in corn and wheat but not different from barley and sorghum. It was also observed that hybrid rye contained more total dietary fiber (**TDF**) than wheat, corn, and sorghum, and the apparent total tract digestibility (**ATTD**) of TDF was greater in hybrid rye than in all other grains tested. The hindgut disappearance of GE was also greatest in hybrid rye, thus, fermentation of fiber contributed a greater proportion to overall energy production when hybrid rye was fed. Overall, the digestibility of DM, starch, and GE was greater in corn than in rye, but the fiber in hybrid rye may offer health benefits to pigs that are not attained by feeding corn.

Swine producers and nutritionists may use data generated from this research to formulate diets with hybrid rye based on additive digestibility values: SID of AA, STTD of P, and ME. These data will also be used as a foundation to formulate diets in future experiments to evaluate performance and determine the maximum inclusion rate when hybrid rye is fed to nursery, growing, and finishing pigs, as well as gestating and lactating sows.